WADC TECHNICAL REPORT 53-336
PART 4

THE CREEP PROPERTIES OF METALS UNDER INTERMITTENT STRESSING AND HEATING CONDITIONS

Part 4. Creep Results for Alclad 7075-T6 Aluminum Alloy and Comparison with Results for Other Materials

N. H. G. DANIELS
H. B. MASUDA
JOHN E. DORN

UNIVERSITY OF CALIFORNIA

MAY 1956

WRIGHT AIR DEVELOPMENT CENTER

NOTICES

WADC TECHNICAL REPORT 53-336
PART 4

THE CREEP PROPERTIES OF METALS UNDER INTERMITTENT STRESSING AND HEATING CONDITIONS

Part 4. Creep Results for Alclad 7075-T6 Aluminum Alloy and Comparison with Results for Other Materials

N. H. G. DANIELS
H. B. MASUDA
JOHN E. DORN

UNIVERSITY OF CALIFORNIA

MAY 1956

MATERIALS LABORATORY
CONTRACT No. 33(038)-11502
PROJECT No. 7360

WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Carpenter Litho & Prtg. Co., Springfield, O.
500 - July 1956

FOREWORD

This report was prepared by the Institute of Engineering Research, University of California, Berkeley, California, under USAF Contract No. AF 33(038)-11502. The contract was conducted under Project No. 7360, "Materials Analysis and Evaluation Techniques", Task No. 73605, "Design Data for Metals", formerly RDO No. 614-13, "Design and Evaluation Data for Structural Metals", and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Mr. E. L. Horne acting as project engineer. This report covers work accomplished between October 1953 and October 1954.

The authors wish to express their appreciation of the help given by Mr. L. A. Shepard, who had been associated with previous work on the subject at the University of California

ABSTRACT

A study was made of the creep properties of clad aluminum alloy 75S-T6 under intermittent heating and loading conditions at 300°F and 600°F. A few tests were also conducted at 450°F under intermittent heating conditions.

The results were correlated by means of the empirical functional equation

$$\varepsilon = F\left\{t f(\sigma)\right\}$$

where ε = total strain
t = time
σ = stress
F = strain function
f = stress function.

As suggested in previous reports, the function f was shown to be approximately independent of strain and of the type of intermittent testing cycle. The prediction of intermittent condition creep data can therefore be carried out from a knowledge of the constant load isothermal data, and a single test under the intermittent condition.

A review of the literature has shown that although in a significant proportion of cases the above analysis can be used successfully, the function f often varies considerably with strain, and in some instances is not independent of the type of intermittent condition. Nevertheless even the approximate prediction of intermittent creep data by flexible use of the method is likely to be of value.

The test results were also compared on a basis of net time at temperature under load. It appears that any intermittent cycle permitting recovery and overaging of the material in the absence of load has a deleterious effect on its creep resistance. Under other intermittent conditions the creep of the material is approximately the same on a net time basis as its creep under steady load isothermal conditions.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. R. Whitmore

M. R. WHITMORE
Technical Director
Materials Laboratory
Directorate of Research

TABLE OF CONTENTS

	Page
Introduction	1
Material, Equipment, and Test Methods	4
Test Results	8
1. Results at 300°F	8
2. Results at 450°F	22
3. Results at 600°F	22
Discussion of Test Results	34
1. Methods of Analytical Approach	34
2. Analysis of 300°F Data	37
(a) Net Time Approach	37
(b) Analytical Correlation and Prediction	40
3. Analysis of 450°F Data	49
(a) Net Time Approach	49
(b) Analytical Correlation and Prediction	53
4. Analysis of 600°F Data	53
(a) Net Time Approach	53
(b) Analytical Correlation and Prediction	58
Evaluation of Analytical Methods	62
1. Introduction	62
2. Criteria for Evaluation	63
3. Methods of Evaluation	67
4. Application to Steady Load-Isothermal Creep Data	68
5. Application to Published Intermittent Condition Creep Data	70
(a) Magnesium Alloy FS-1H	71
(b) 24S-T3 Aluminum Alloy	74
(c) Low Carbon N-155 Alloy	76
(d) Inconel X	76
(e) Titanium Alloy RC 130-A	79
(f) Type 321 Stainless Steel	79
6. Results of Evaluation of Analytical Method	82
Conclusions	86
Bibliography	89

LIST OF TABLES

Table		Page
I.	Creep of Clad Aluminum Alloy 75S-T6 at 300°F under Steady and Intermittent Conditions. Times to Various Total Strains . . .	10
II.	Creep of Clad Aluminum Alloy 75S-T6 at 300°F under Steady and Intermittent Conditions. Times to Various Creep Strains . . .	12
III.	Creep of Clad Aluminum Alloy 75S-T6 at 450°F. Steady Stress, Intermittent Temperature 1 Hr./1 Hr., Cycle 3. Total Times to Reach Various Total Strains	23
IV.	Creep of Clad Aluminum Alloy 75S-T6 at 450°F. Steady Stress, Intermittent Temperature 1 Hr./1 Hr., Cycle 3. Total Times to Reach Specified Creep Strains	24
V.	Creep of Clad Aluminum Alloy 75S-T6 at 600°F under Steady and Intermittent Conditions. Total Times to Reach Various Total Strains	27
VI.	Comparison of Average Net Times (Net t_g) to Reach Specified Strains for Various Intermittent Conditions. Creep of 75S-T6 at 300°F	38
VII.	Analysis of Creep Data for 75S-T6 at 300°F. Cycle 3	42
	(a) Total Strain Basis	42
	(b) Creep Strain Basis	43
	(c) Average K_g Values for Steady Load Steady Temperature Tests	44
VIII.	Values of K_g at Various Stresses, Total Strains, and Intermittent Conditions. Creep of 75S-T6 at 300°F	47
	(a) Total Strain Basis	47
	(b) Creep Strain Basis	48
IX.	Average Values of K_{ex} and K_g for Various Stresses and Intermittent Conditions. Creep of 75S-T6 at 300°F	51
X.	K_g Values for Various Stresses, Strains, and Intermittent Conditions. Creep of 75S-T6. 450°F. Cycle 3	54
	(a) Total Strain Basis	54
	(b) Creep Strain Basis	54
XI.	Comparison of Average Net Times (Net t_g) to Reach Specified Strains for Various Cyclic Conditions. Creep of 75S-T6 at 600°F	57

Table		Page
XII.	Values of K_s at Various Stresses, Total Strains, and Intermittent Conditions. Creep of 75S-T6 at 600°F	59
XIII.	Average Values of K_{ex} and K_s for Various Stresses and Intermittent Conditions. Creep of 75S-T6 at 600°F	60
XIV.	Comparison of Experimental and Calculated Creep Data for Steady Load Isothermal Creep of 75S-T6 at 300°F	66
	(a) Comparison on Time Basis	66
	(b) Comparison on Stress Basis	66
XV.	Average K Factor Values for Various Stresses and Intermittent Conditions. Creep of FS-1H Magnesium Alloy	73
	(a) 300°F	73
	(b) 450°F	73
XVI.	K Factor Values for Various Stresses and Intermittent Conditions. Creep of 24S-T3 Aluminum Alloy	75
	(a) 450°F	75
	(b) 600°F	75
XVII.	K Factor Values for Various Stresses, Strains, and Intermittent Conditions. Creep of Low Carbon N-155 Alloy	77
	(a) 1350°F	77
	(b) 1500°F	78
XVIII.	Average K Factor Values for Various Stresses and Intermittent Conditions. Creep of Inconel X	80
XIX.	Average K Factor Values for Various Stresses and Intermittent Conditions. Creep of Titanium Alloy RC-130A	81
XX.	Average K Factor Values for Various Stresses and Intermittent Conditions. Creep of Type 321 Stainless Steel	83
	(a) 120°F	83
	(b) 1350°F	83

LIST OF ILLUSTRATIONS

Figure		Page
1.	Diagramatic Representation of Cycles of Intermittent Loading and/or Heating	7
2.	Creep of 75S-T6. 300°F. Steady Load and Temperature	14
3.	Creep of 75S-T6. 300°F. Steady Load, Intermittent Temperature. 1 Hr./1 Hr. Cycle 3	14
4.	Creep of 75S-T6. 300°F. Steady Temperature, Intermittent Load. 1 Hr./1 Hr. Cycle 1	15
5.	Creep of 75S-T6. 300°F. Steady Temperature, Intermittent Load. $1\frac{1}{2}$ Hr./$\frac{1}{2}$ Hr. Cycle 2	15
6.	Creep of 75S-T6. 300°F. Intermittent Load and Temperature. In Phase. 1 Hr./1 Hr. Cycle 5	16
7.	Creep of 75S-T6. 300°F. Intermittent Load and Temperature. Out of Phase. 1 Hr./1 Hr. Cycle 6	16
8.	Creep of 75S-T6. 300°F. Intermittent Load and Temperature. In Phase. $1\frac{1}{2}$ Hr./$\frac{1}{2}$ Hr. Cycle 7	17
9.	Creep of 75S-T6. 300°F. Intermittent Load and Temperature. Out of Phase. $1\frac{1}{2}$ Hr./$\frac{1}{2}$ Hr. Cycle 8	17
10.	Creep of 75S-T6. 300°F. Stress/Log Time Curves. Steady Load and Temperature	18
11.	Creep of 75S-T6. 300°F. Stress/Log Time Curves. Steady Load, Intermittent Temperature. 1 Hr./1 Hr. Cycle 3	18
12.	Creep of 75S-T6. 300°F. Stress/Log Time Curves. Steady Temperature, Intermittent Load. 1 Hr./1 Hr. Cycle 1	19
13.	Creep of 75S-T6. 300°F. Stress/Log Time Curves. Steady Temperature, Intermittent Load. $1\frac{1}{2}$ Hr./$\frac{1}{2}$ Hr. Cycle 2	19
14.	Creep of 75S-T6. 300°F. Stress/Log Time Curves. Intermittent Load and Temperature. In Phase. 1 Hr./1 Hr. Cycle 5	20
15.	Creep of 75S-T6. 300°F. Stress/Log Time Curves. Intermittent Load and Temperature. Out of Phase. 1 Hr./1 Hr. Cycle 6	20
16.	Creep of 75S-T6. 300°F. Stress/Log Time Curves. Intermittent Load and Temperature. In Phase. $1\frac{1}{2}$ Hr./$\frac{1}{2}$ Hr. Cycle 7	21

Figure		Page

17. Creep of 75S-T6. 300°F. Stress/Log Time Curves. Intermittent Load and Temperature. Out of Phase. 1½ Hr./½ Hr. Cycle 8 21

18. Creep of 75S-T6. 450°F. Steady Load, Intermittent Temperature. 1 Hr./1 Hr. Cycle 3 25

19. Creep of 75S-T6. 450°F. Stress/Log Time Curves. Steady Load, Intermittent Temperature. 1 Hr./1 Hr. Cycle 3 26

20. Creep of 75S-T6. 600°F. Steady Load and Temperature 28

21. Creep of 75S-T6. 600°F. Steady Load, Intermittent Temperature 28

22. Creep of 75S-T6. 600°F. Intermittent Load and Temperature. In Phase. 1 Hr./1 Hr. Cycle 5 29

23. Creep of 75S-T6. 600°F. Intermittent Load and Temperature. Out of Phase. 1 Hr./1 Hr. Cycle 6 29

24. Creep of 75S-T6. 600°F. Intermittent Load and Temperature. In Phase. 1½ Hr./½ Hr. Cycle 7 30

25. Creep of 75S-T6. 600°F. Intermittent Load and Temperature. Out of Phase. 1½ Hr./½ Hr. Cycle 8 30

26. Creep of 75S-T6. 600°F. Stress/Log Time Curves. Steady Load and Temperature. 31

27. Creep of 75S-T6. 600°F. Stress/Log Time Curves. Steady Load, Intermittent Temperature. 1 Hr./1 Hr. Cycle 3 31

28. Creep of 75S-T6. 600°F. Stress/Log Time Curves. Intermittent Load and Temperature. In Phase. 1 Hr./1 Hr. Cycle 5 32

29. Creep of 75S-T6. 600°F. Stress/Log Time Curves. Intermittent Load and Temperature. Out of Phase. 1 Hr./1 Hr. Cycle 6 32

30. Creep of 75S-T6. 600°F. Stress/Log Time Curves. Intermittent Load and Temperature. In Phase. 1½ Hr./½ Hr. Cycle 7 33

31. Creep of 75S-T6. 600°F. Stress/Log Time Curves. Intermittent Load and Temperature. Out of Phase. 1½ Hr./½ Hr. Cycle 8 33

32. Hypothetical Deformation During Various Types of Cycles . . . 41

Figure | Page

33. Prediction of Creep Data. 75S-T6. 300°F. Cycle 3 46

(a) Total Strain/Total Time Curves 46
(b) Creep Strain/Total Time Curves 46

34. Variation of K with Stress and Strain. 75S-T6. 300°F. Cycle 3 50

(a) K_{ax} 50
(b) K_g 50

35. Variation of K_g with Stress and Strain. 75S-T6. 450°F. Cycle 3 55

36. Prediction of Creep Data. 75S-T6. 450°F. Cycle 3. Total Strain/Total Time Curves 55

37. Variation of K Values with Stress and Strain. 75S-T6. 600°F. Cycle 3 61

38. Prediction of Creep Data. 75S-T6. 600°F. Cycle 3. Total Strain/Total Time Curves 61

39. Actual and Calculated Stress/Log Time Curves. 75S-T6. 300°F. Steady Load and Temperature 65

40. Creep of FS-1H Magnesium Alloy. 300°F. Intermittent Load 1 Hr. On/1 Hr. Off. Experimental and Predicted Curves. . . . 72

41. Experimental and Predicted Creep Curves. Type 321 Stainless Steel. Steady Load and Temperature. 1350°F. 84

42. Experimental and Predicted Creep Curves. Type 321 Stainless Steel. Intermittent Heating. 1350°F. 84

ERRATA

Aluminum and titanium alloy designations as referenced in this report should be replaced by the current designations as given below:

Old Designation	Current Designation
75S-T6	7075-T6
24S-T3	2024-T3
RC-130A	C-110M
2S	1100
4S	3004
63S	6063-T6

INTRODUCTION

It is only on rare occasions that the design engineer has data available on the behavior of appropriate materials under the precise conditions of the intended usage, and it is often impracticable to conduct laboratory tests simulating closely the known or expected variation in stress, temperature, and environment to which the part will be exposed during its service life. This is the case for aircraft structural and engine components subjected to such stresses and temperatures as to make creep one of the limiting design criteria. While almost all of the considerable body of creep data collected for a wide variety of materials is derived from isothermal tests conducted under steady constant load, the actual use of the material may involve a highly irregular and complex history of stress and temperature conditions. It had been considered sufficient to design conservatively on the basis of the isothermal steady load tensile creep properties even at the expense of some inefficiency but indications were found[1,2,3] that cyclic conditions of stressing or heating could in some cases cause accelerated creep and premature failure such that the design was not in fact conservative.

The present investigation was therefore undertaken to ascertain what effects might be encountered when materials were subjected to creep under intermittent loading or heating, or combinations of intermittent loading and heating. A previous report[4] has described the results of intermittent stress tests on clad aluminum alloys 75S-T6 and 24S-T3 at 300°F, 450°F and 600°F, and on commercial purity titanium at 400°F. Intermittent temperature tests on 75S-T6 and 24S-T3 alloys at 450°F[5], and combined intermittent stress and temperature tests on 75S-T6 alloy at 450°F[6] have also been reported. The work described in the present report was concerned with intermittent temperature, and combined intermittent stress and temperature tests on clad aluminum alloy 75S-T6 at 300°F and 600°F, and some additional intermittent temperature tests at 450°F.

In the earlier reports referred to above, it was concluded that under the test conditions employed, intermittent temperature, or in phase cycles of intermittent stressing and temperature do not greatly affect the creep properties of the alloys tested when the deformation and rupture characteristics are compared with steady load isothermal creep, as judged on a basis of net time under load at the test temperature. Subjecting the material to intermittent stressing at a steady temperature or to out of phase combined cycles of load and temperature (where the test piece is at test temperature in the absence of load for part of the cycle) does, however, produce accelerated creep and earlier rupture as compared with steady load isothermal conditions, again using the above net time criterion.

Extensive work at Cornell Aeronautical Laboratories, Inc.[7,8] on the creep behavior of a variety of alloys under intermittent stressing or heating conditions has shown that creep can be either accelerated or retarded according to the relative influence exerted by such factors as overaging, crystal recovery, ductility changes, creep recovery, and thermal stress effects.

During the course of the previous work in these laboratories some success was achieved in correlating and predicting both steady condition and intermittent condition creep data by the use of the functional relation

$$\varepsilon = F\left\{t\, f(\sigma)\right\} \qquad (1)$$

where ε = total strain

t = time

σ = stress

F = strain function

f = stress function.

Plotting strain against log time at various stresses for creep under steady or intermittent conditions gave, for any particular test temperature and type of test, a series of more or less homologous creep curves which differed primarily in their displacement along the log time axis. Then, if t_s were the time to reach a certain strain at a selected standard stress σ_s, the time, t, to reach the same strain at some other stress σ would be given by

$$\log t = \log t_s + \log \left\{ \frac{f(\sigma)}{f(\sigma_s)} \right\} \tag{2}$$

or

$$t_s = K_{(\sigma \sigma_s)} t \tag{3}$$

By using this relation, a single composite creep curve could be drawn, representing the creep behavior of the material at one temperature under a specified steady or intermittent condition, thus permitting a simple comparison of the effects of various types of cycle. The value of $K_{(\sigma \sigma_s)}$ obtained for the same stresses was only slightly dependent on the strain, and similar values were found for steady stress isothermal creep and for the various types of intermittent test cycle. Thus the function F contains the effect of the cyclic condition, and the stress function f is approximately independent of strain or the type of test. Consequently if one intermittent stress test were run at the standard stress σ_s, the time t_i to achieve the same strain at any other intermittent stress, σ, for the same cycle could be determined from

$$t_{(s)_i} = K_{(\sigma \sigma_s)_i} t_i = K_{(\sigma \sigma_s)_c} t_i \tag{4}$$

where $K_{(\sigma\sigma_s)c} = \frac{t_{(s)c}}{t_{(\sigma)c}}$ and is determined from two steady stress creep curves, and $t_{(s)i}$ from the single intermittent stress creep curve at the standard stress σ_s . Furthermore, if tests at a series of stresses under steady load isothermal conditions are already available over a suitable range, intermediate values of $K_{(\sigma\sigma_s)c}$ may be interpolated from a plot of log $K_{(\sigma\sigma_s)c}$ against log σ where σ_s has been chosen appropriately.

The additional test results obtained under various intermittent conditions, and presented in this report, have been analyzed both on the basis of the net time under load at test temperature and on the basis of the functional equation (1). Predicted creep curves calculated by the use of equations (2) and (4) using K values averaged over various strains up to and including fracture are compared with the experimental results.

Universal application of this empirical method of analysis and prediction should not be expected. This is borne out by the later section of this report dealing with a general evaluation of the method. Nevertheless, in view of the paucity of experimental creep data under conditions of intermittent loading and heating, even the approximate quantitative prediction of such data was considered a worthwhile goal, and the analytical work summarized in this report has been prosecuted from this point of view.

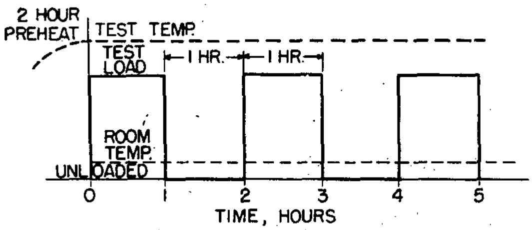
MATERIAL, EQUIPMENT AND TEST METHODS

All tests in the present series were conducted on clad aluminum alloy 75S-T6 (Government Specification An-A-13) of the same batch as that used in earlier work[4,5,6] in these laboratories. Details of the analysis and room temperature tensile properties have been reported previously.[4] The material was supplied in the form of a number of 10" x 20" sheets of the same production batch, and specimens were cut from these parallel to the rolling direction, the sheets being numbered consecutively as they were taken from the box.

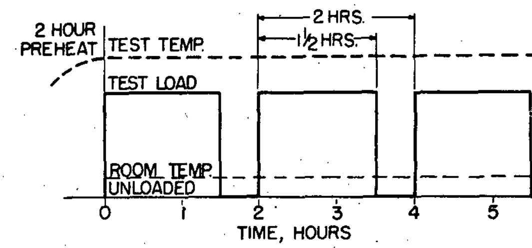
The equipment used in these tests was that which has been previously described,[9,10] with the later modification[6] in which the heat capacity of the furnaces was reduced, so that they could meet more easily the short heating period required in tests involving the use of intermittent heating conditions. In consequence, the initial heating of the test piece before the first test cycle took place more rapidly than previously, and in order to compensate approximately for this, the first load was applied two hours, instead of three hours, after the initial heating of the test piece was commenced. A check of this compensation was made by testing equivalent specimens at the same stress using the new standard two hours initial heating period in one case, and an initial heating, controlled by hand to simulate the earlier three hour procedure, in the other case. The creep curves and fracture times obtained were practically identical in the two cases and the use of the revised two hour initial heating period was therefore considered justified.

During the steady high temperature portion of each cycle, the temperature of the specimen was maintained constant within $\pm 3^{\circ}$F of the reported test temperature, and was measured by two iron-constantan thermocouples held in place on the specimen near the extensometer gauge points by adhesive glass tape or string. Sometimes a third thermocouple in the center of the gauge length was also employed. Stresses were determined to within an accuracy of 25 psi, and the creep extensions were measured on a two inch gauge length to 0.01% strain. In order to avoid the inconsistencies which would be caused by variable or inaccurate initial strain measurements in such data as the time taken to reach a given strain, all creep curves were corrected to standard values of the initial strain corresponding to the particular test stress. These values were obtained either from stress-strain curves determined at the test temperature in the creep testing machine using manual incremental loading and a mechanical extensometer, or as the mean of the initial deformations recorded for the stress in question in a large number of creep tests.

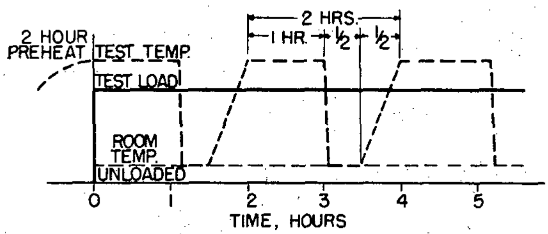
The appropriate sequence of intermittent heating and stressing was started at the time of initial application of the test load, and all times were taken from this reference point. Loading and unloading times for both steady and intermittent load tests were approximately two minutes. Intermittent load cycles, either alone or in combination with intermittent temperature cycles, of 1 hr. and $1\frac{1}{2}$ hrs. respectively out of a total cycle of two hours were used. For tests involving intermittent heating conditions the same periods of 1 hr. and $1\frac{1}{2}$ hrs. out of a total cycle time of 2 hrs. were used during which the specimen was maintained at the test temperature. In the former case $\frac{1}{2}$ hr. was allowed for heating to test temperature, the specimen being cooled to room temperature in 6 mins. and maintained at room temperature for 24 mins. In the latter case ($1\frac{1}{2}$ hrs. at temperature per 2 hr. cycle), heating to the test temperature was accomplished in 20 mins. the remaining 10 mins. being spent at room temperature or cooling down to it. For the combined intermittent heating and stressing tests, cycles with the on-load period both in phase and out of phase with the period of constant elevated temperature were used, tests being conducted for both 1 hr. and $1\frac{1}{2}$ hr. cycles of load and temperature. The eight types of cycle are shown diagramatically in Fig. 1, cycle 4 being included for completeness although it was not used in the test series



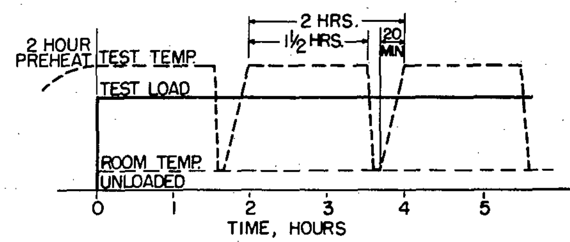
CYCLE 1. STEADY TEMPERATURE, INTERMITTENT LOAD - 1 HR./1 HR.



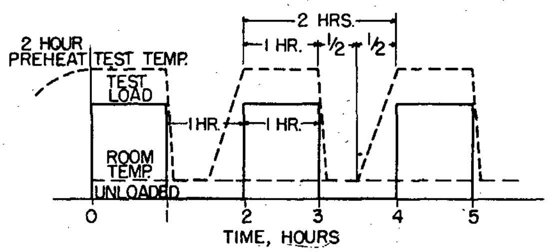
CYCLE 2. STEADY TEMPERATURE, INTERMITTENT LOAD - 1½ HRS./½ HR.



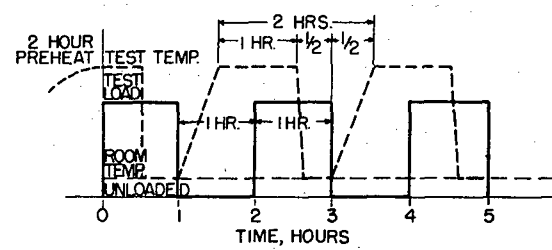
CYCLE 3. INTERMITTENT HEATING, STEADY LOAD - 1 HR./1 HR.



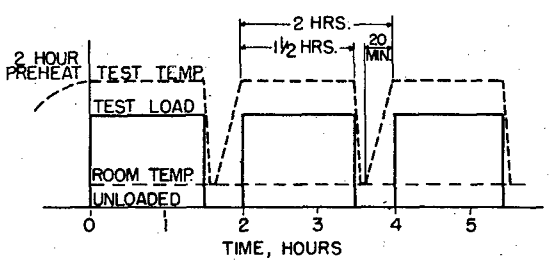
CYCLE 4. INTERMITTENT HEATING, STEADY LOAD - 1½ HRS./½ HR.



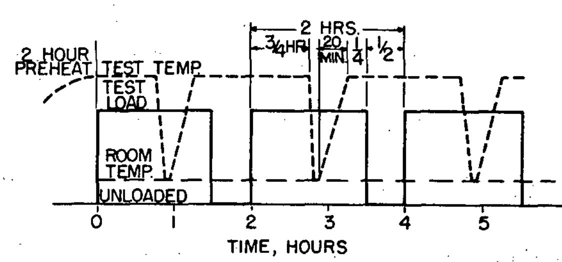
CYCLE 5. COMBINED INTERMITTENT HEATING AND STRESSING IN PHASE - 1 HR./1 HR.



CYCLE 6. COMBINED INTERMITTENT HEATING AND STRESSING OUT OF PHASE - 1 HR./1 HR.



CYCLE 7. COMBINED INTERMITTENT HEATING AND STRESSING IN PHASE - 1½ HRS./½ HR.



CYCLE 8. COMBINED INTERMITTENT HEATING AND STRESSING OUT OF PHASE - 1½ HRS./½ HR.

FIG. 1 DIAGRAMATIC REPRESENTATION OF CYCLES OF INTERMITTENT LOADING AND/OR HEATING.

covered by this report.

TEST RESULTS

The test results obtained during the period covered by this report are presented in Tables I-V inclusive and in Figs. 2-31 inclusive. All times given were the total elapsed times, the creep curves for intermittent conditions being drawn as the envelope of readings taken at the end of the constant temperature, under load period of each cycle. At this time, the temperature conditions approximated closely to equilibrium, and the strain readings were therefore most consistent. At other intermediate points on the cycle the strain readings may be influenced by differential expansion between the outer tube and inner rod of the extensometer as heating or cooling is taking place.

1. Results at 300°F.

The data already presented[4] at 300°F on clad aluminum alloy 75S-T6 were extended in the presented series of creep tests to the cases of intermittent heating under steady load, and combined intermittent loading and intermittent temperature. Only one cycle, of one hour at steady elevated temperature per total cycle of two hours, (Cycle 3) was used in the intermittent heating case. For the tests under conditions of combined intermittent heating and loading, two time cycles of 1 hr. and $1\frac{1}{2}$ hrs. on time per 2 hr. cycle were employed and for both time schedules tests were conducted with the loading both in phase (cycles 5 and 7) and out of phase (cycles 6 and 8) with the heating. In reviewing the results of these tests it was found that certain incompatibilities existed between them and the early isothermal steady load and intermittent load data using 1 hr. and

1½ hrs. on times per 2 hr. cycle. (Cycles 1 and 2). Consequently these three series of tests were repeated to ensure that a complete series of comparable creep tests were available under the eight combinations of steady or intermittent stress or temperature. At the end of the test program, a repeat series (Series II) of tests at 300°F under cycle 7 conditions were done, using a sheet of material different from that used for the previous series (Series I). The results obtained indicated a greater creep strength, particularly at low stresses, than the Series I results shown in Fig. 8, the Series II results being compatible with the earlier data[4] rather than with the present Series I. It seems probable, therefore, that the differences between the earlier data, and that presently reported, may well be ascribed to slight differences between different sheets of the test material stock. The Series II results under cycle 7 conditions are included at the foot of Tables I and II.

The results obtained are reported in Table I in terms of the total elapsed test times at the various stresses to reach specified total strains. Table II contains similar data related to specified creep strains. The creep strains were obtained by subtracting from the total extension measured by the equipment the best values for the strain taking place on first application of the load the remainder being the time dependent or creep strain portion of the deformation. Figs. 2-9 inclusive show the families of creep curves obtained under the various steady and intermittent testing conditions at 300°F. The data of Tables I and II have been replotted in Figs. 10-17 inclusive to give stress versus log-time design curves for specified values of the total or creep strains.

TABLE I

Creep of Clad Aluminum Alloy 75S-T6 at 300°F under Steady and Intermittent Conditions Total Times to Reach Various Total Strains

Type of Test	Stress psi	Total Time (Hrs.) to Reach Total Strains of 0.5%	1.0%	1.5%	2.0%	3.0%	Fracture	Elong. % on 2" at Fracture
Steady Load and Temperature	42,000	[0.2]	8¼	14	16¾	--	19.9	2.54
	38,500	[0.3]	25	46½	53½	58	58.6	3.56
	35,500	[0.4]	47	67	76	80¼	80.3	3.32
	33,500	22	84	104	112½	--	115.4	2.64
	33,500	8½	95	123	127	--	146.4	2.72
	31,500	25	132	159	168	--	169.8	2.72
Steady Temperature Intermittent Load 1 Hr./1 Hr. Cycle 1	42,000	--	17.5	26	30	33½	36.2	5.68
	38,500	< ½	46	59	66	71	72.3	3.34
	35,500	5	87	--	--	--	94.7	1.22
	35,500	5	91	115	124	129	130.1	3.64
	33,500	30	143	167½	176	180½	180.8	3.15
	31,500	43	200	240	252½	--	256.1	2.92
Steady Temperature Intermittent Load 1½ Hr./½ Hr. Cycle 2	42,000	--	17	27	32	36½	38.7	3.86
	38,500	1	40½	54½	61	65	66.9	6.18
	35,500	6	75½	94	102	108½	109.3	4.44
	35,500	5½	76½	97	106	110½	111	3.69
	33,500	14	112	137	148	154	155	5.72
	31,500	27	142	174	188	--	196.3	2.67
Steady Load Intermittent Temp. 1 Hr./1 Hr. Cycle 3	42,000	[0.1]	16	30	39	48½	54.4	6.08
	38,500	1	56	79	88½	--	94.2	2.48
	35,500	0	113	145	160	--	168.3	2.44
	33,500	29	176	219	[230]	--	--	--
	31,500	70	--	--	--	--	--	--
Intermittent Load and Temperature In Phase 1 Hr./1 Hr. Cycle 5	42,000	[0.1]	22	36	43	49	50.7	3.50
	38,500	1	76½	102½	114	--	118.8	2.40
	35,500	8	126	157	171	182½	182.8	3.42
	33,500	12	170	223	245	--	--	--
	31,500	72	--	--	--	--	--	--
Intermittent Load and Temperature Out of Phase 1 Hr./1 Hr. Cycle 6	42,000	[0.1]	23	35	41	46	46.6	3.16
	38,500	1½	80	112	123	130	132.3	4.10
	35,500	17	157	187	197	204	204.4	3.40
	33,500	40	--	--	--	--	--	--
	33,500	33	[260]	--	--	--	--	--
	31,500	70	[335]	--	--	--	--	--

TABLE I (Cont'd.)

Intermittent Load	42,000	2	30	$30\frac{1}{2}$	41	48	49.2	3.12
and Temperature	38,500	--	43	55	$60\frac{1}{2}$	65	66	3.94
In Phase	35,500	$2\frac{1}{2}$	110	144	158	$166\frac{1}{2}$	167	3.43
$1\frac{1}{2}$ Hr./$\frac{1}{2}$ Hr.	33,500	24	130	159	--	--	165.5	1.74
Cycle 7 (Series I)	31,500	30	170	214	225	--	--	--
Intermittent Load	42,000	$\frac{1}{2}$	16	24	28	--	32.6	3.00
and Temperature	38,500	$< \frac{1}{2}$	50	66	74	80	81.5	3.34
Out of Phase	35,500	3	94	$120\frac{1}{2}$	131	--	137.3	2.46
$1\frac{1}{2}$ Hr./$\frac{1}{2}$ Hr.	33,500	10	136	176	--	--	192.8	1.98
Cycle 8	31,500	49	193	229	245	--	247.2	2.13
Intermittent Load	42,000	--	14	$25\frac{1}{2}$	31	$33\frac{1}{2}$	35.0	3.72
and Temperature	38,500	$\frac{3}{4}$	48	68	76	$80\frac{1}{2}$	84.2	4.17
In Phase	35,500	2	98	127	140	146	152.9	3.59
$1\frac{1}{2}$ Hr./$\frac{1}{2}$ Hr.	33,500	19	143	173	187	194	194.9	2.58
Cycle 7	31,500	26	224	[275]	--	--	N.F.	--
Repeat Series II								

[ ] = Extrapolated or Estimated Value

TABLE II

Creep of Clad Aluminum Alloy 75S-T6 at 300°F under Steady and Intermittent Conditions Total Times to Reach Various Creep Strains

Type of Test	Stress psi	Total Times (Hrs.) to Reach Creep Strains of:					
		0.1%	0.2%	0.3%	0.5%	1.0%	2.0%
Steady Load	42,000	½	2	3¾	7½	13	18½
and Temperature	38,500	¾	5	12	24½	44½	56½
	35,500	½	2½	25	37	64	79
	33,500	14	36	56	76	99	115
	31,500	3½	37	72	112	153	169½
Steady Temperature	42,000	--	4	8½	16	25	32
Intermittent Load	38,500	½	12	25	41½	57½	69
1 Hr./1 Hr.	35,500	2	30	53	78	--	--
Cycle 1	35,500	2½	25	47	79	111	126
	33,500	10	57	90	128	163	179
	31,500	13	64	112	172	232	254
Steady Temperature	42,000	--	3	7½	15½	26	34½
Intermittent Load	38,500	1½	11	20	36½	53	64
1½ Hr./½ Hr.	35,500	2½	22	42	67	91	106
Cycle 2	35,500	4	17½	40	67	94	108½
	33,500	2½	32	62	97	132	151½
	31,500	11	41	75	120	166	193
Steady Load	42,000	1	4	8	15½	29	44½
Intermittent Temp.	38,500	2	10	25	49	76	93½
1 Hr./1 Hr.	35,500	6	30	60	100	145	168
Cycle 3	33,500	8	55	98	144	208	--
	31,500	20	103	[180]	--	--	--
Intermittent Load	42,000	0.5	4	10	20	36	46
and Temperature	38,500	2	14	36	71	100	118½
In Phase	35,500	2½	42	68	110	152	178
1 Hr./1 Hr.	33,500	3	32	76	140	213	--
Cycle 5	31,500	11	155	[225]	--	--	--
Intermittent Load	42,000	[0.4]	3	10	21½	34	43
and Temperature	38,500	2½	21	40	70	108	128
Out of Phase	35,500	11	67	96	142	183	201
1 Hr./1 Hr.	33,500	20	97	[150]	--	--	--
Cycle 6	33,500	10	83	142	223	--	--
	31,500	25	107	192	292	[375]	--

TABLE II (Cont'd.)

Intermittent Load and Temperature In Phase 1½ Hr./½ Hr. Cycle 7, Series I	42,000 38,500 35,500 33,500 31,500	-- -- — 5½ 12	4 14 22 46 49	9½ 31 51 74 90	18½ 41 94 115 140	33 53½ 139 154 206	44 63½ 163 -- —
Intermittent Load and Temperature Out of Phase 1½ Hr./½ Hr. Cycle 8	42,000 38,500 35,500 33,500 31,500	1½ -- 2 3 18	4 5 17 31 69	7½ 23 48 64 112	14 44½ 82 93 168	23 64 117 155 222	30½ 77½ 134 [195] —
Intermittent Load and Temperature In Phase 1½ Hr./½ Hr. Cycle 7 Repeat Series II	42,000 38,500 35,500 33,500 31,500	½ 1 1 7 2	2¾ 10 18½ 48 51	5½ 21½ 42 81 111	13 42 83 126 188	25 66 123 167 --	33½ 80 145 192½ --

[ ] = Extrapolated or Estimated Value

NOTE: The following mean values of the initial strains on loading were used in arriving at the data of Tables I and II:

42,000 psi	0.455%
38,500 psi	0.415%
35,500 psi	0.385%
33,500 psi	0.362%
31,500 psi	0.340%

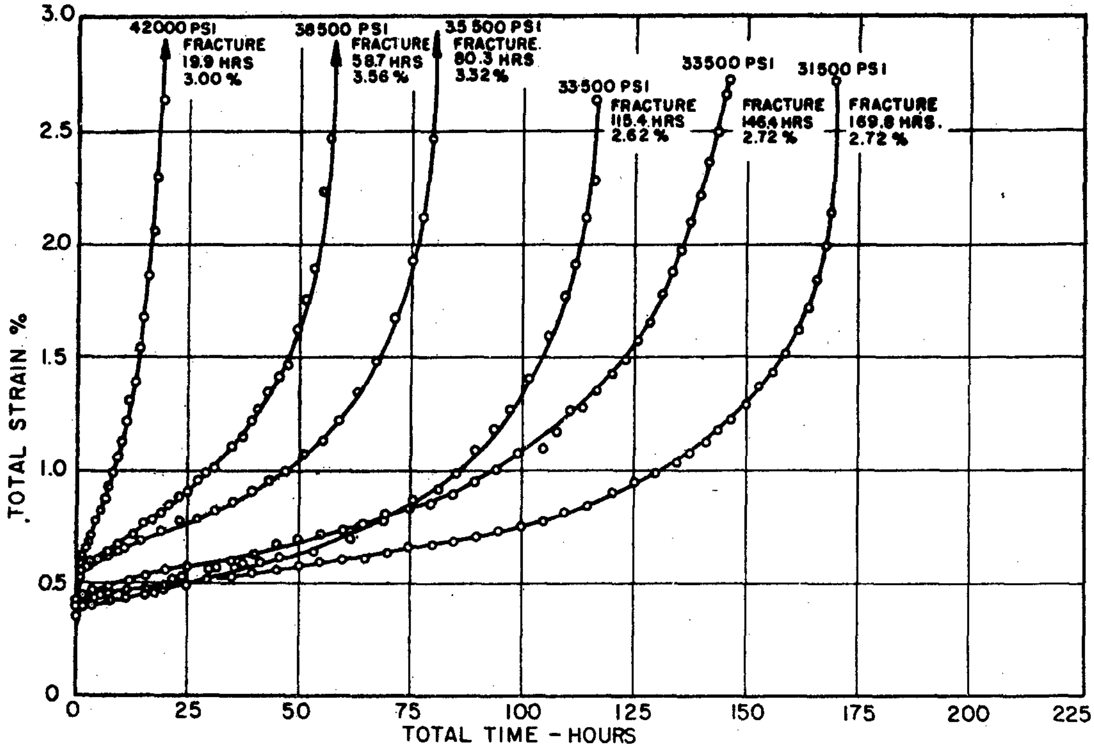


FIG. 2 CREEP OF 75S-T6 300°F STEADY LOAD AND TEMPERATURE

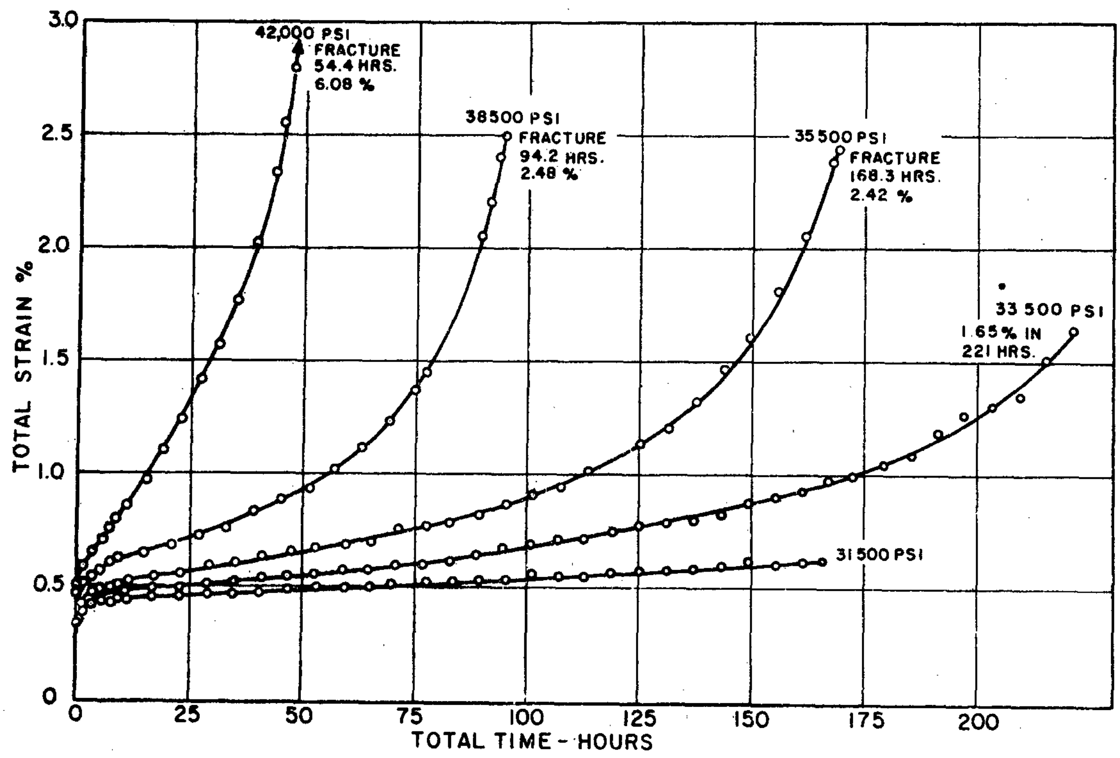


FIG 3 CREEP OF 75S-T6 300° F STEADY LOAD
INTERMITTENT TEMPERATURE 1 HR/1 HR CYCLE 3

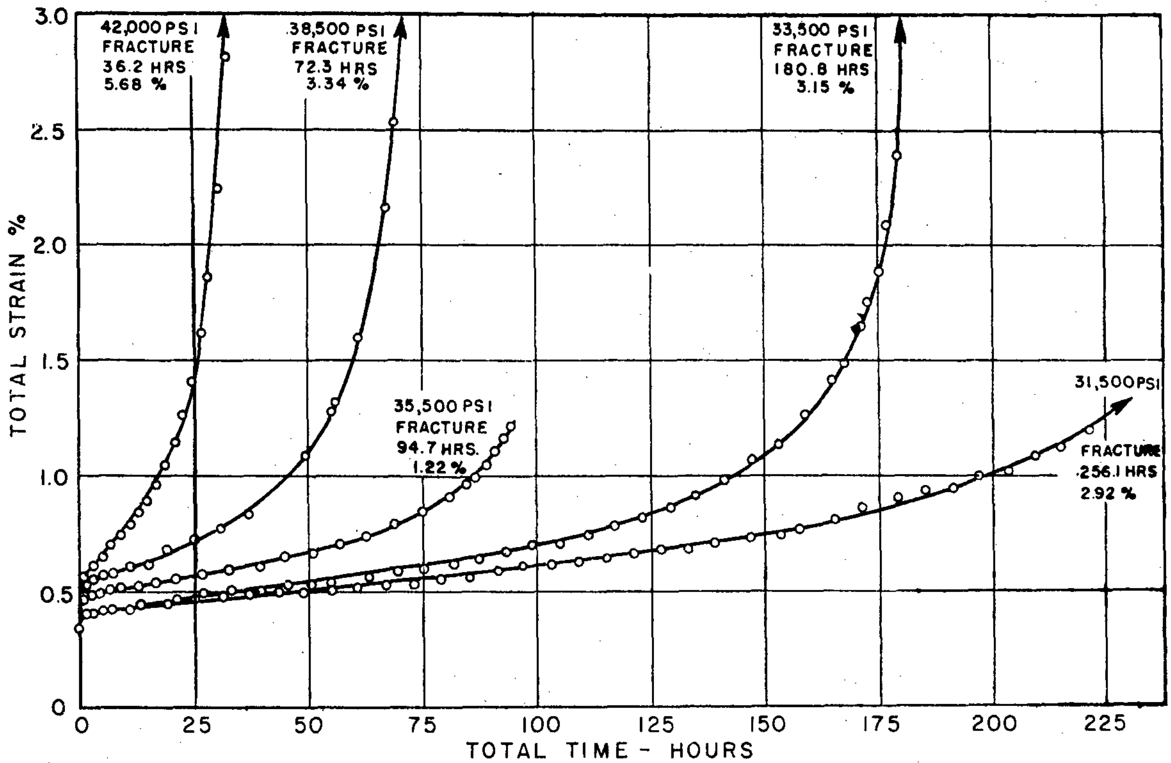


FIG.4 CREEP OF 75S-T6 300°F STEADY TEMPERATURE, INTERMITTENT LOAD 1 HR/1 HR CYCLE 1

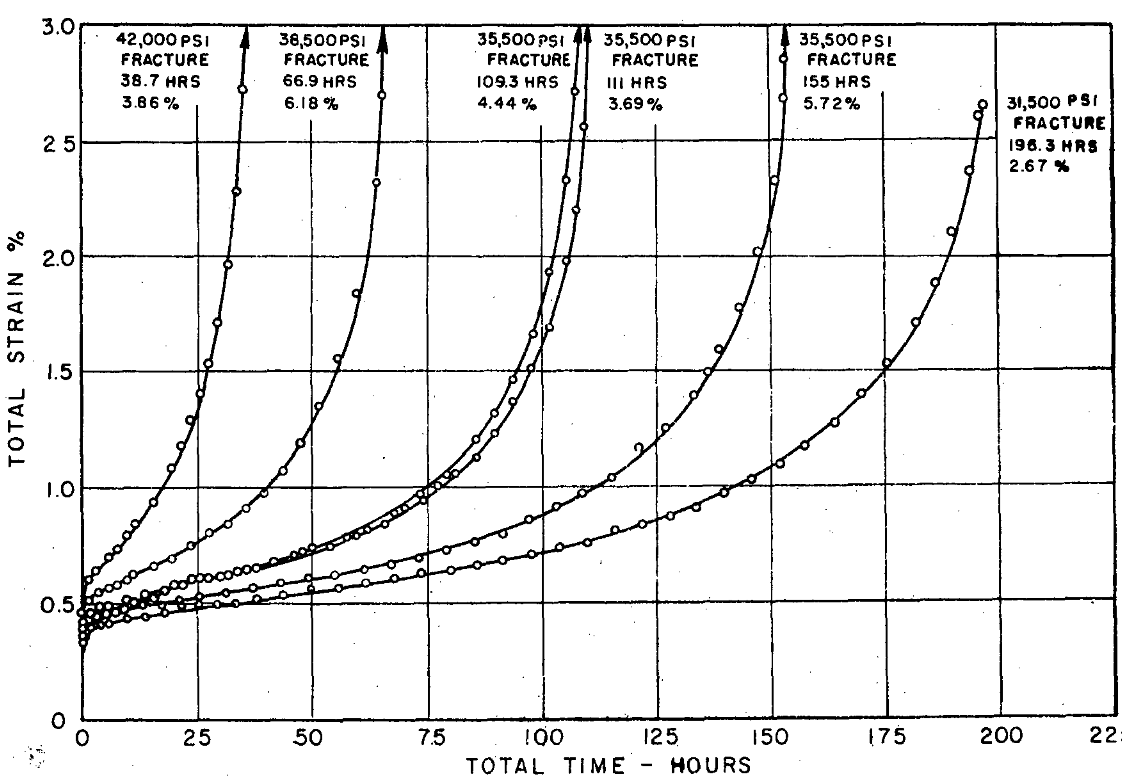


FIG.5 CREEP OF 75 S-T6 300°F STEADY TEMPERATURE, INTERMITTENT LOAD 1½ HR/ ½ HR CYCLE 2

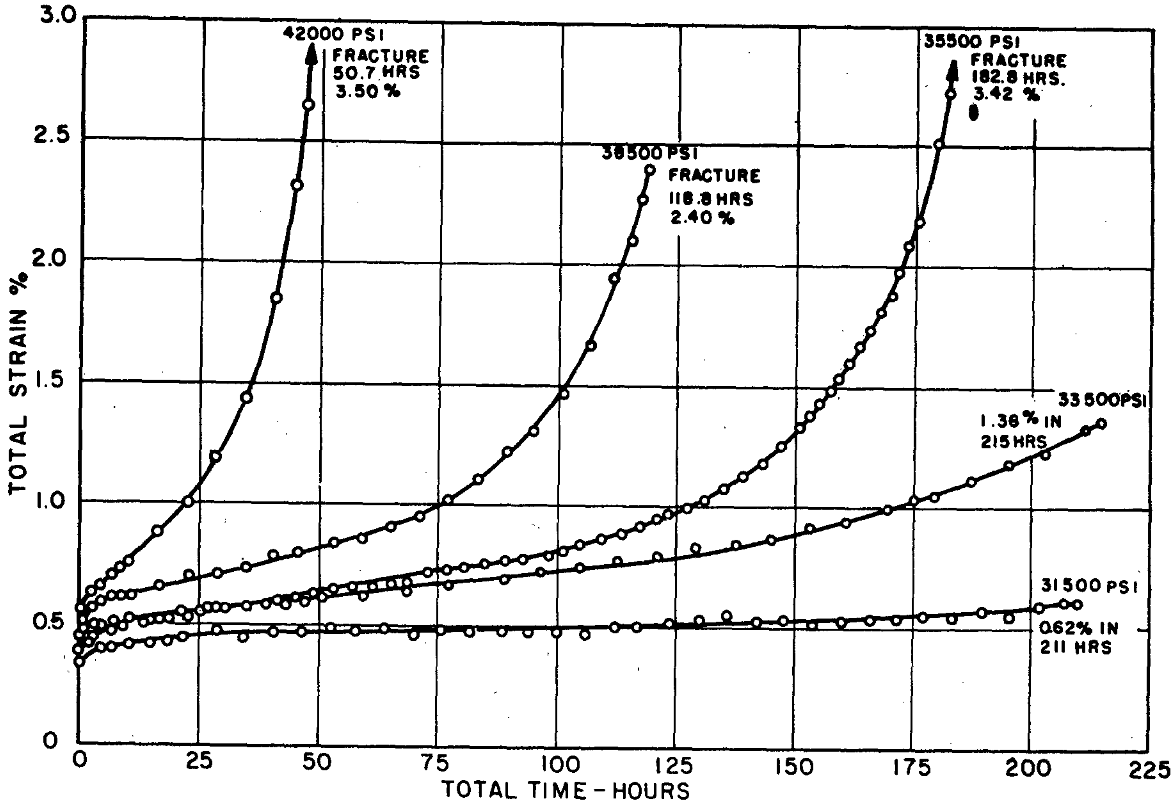


FIG. 6 CREEP OF 75 S-T6 300° F INTERMITTENT LOAD AND TEMPERATURE IN PHASE 1 HR./1 HR. CYCLE 5

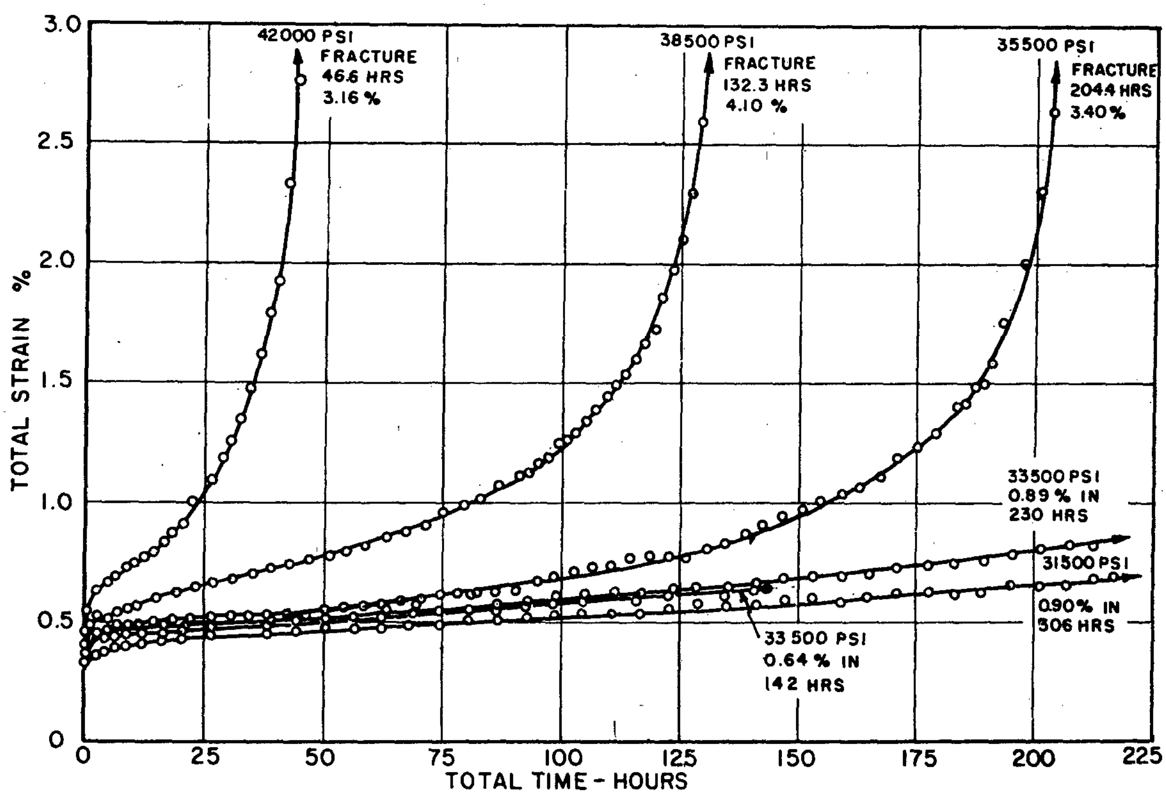


FIG. 7 CREEP OF 75 S-T6 300 °F INTERMITTENT LOAD AND TEMPERATURE OUT OF PHASE 1 HR/1 HR CYCLE 6

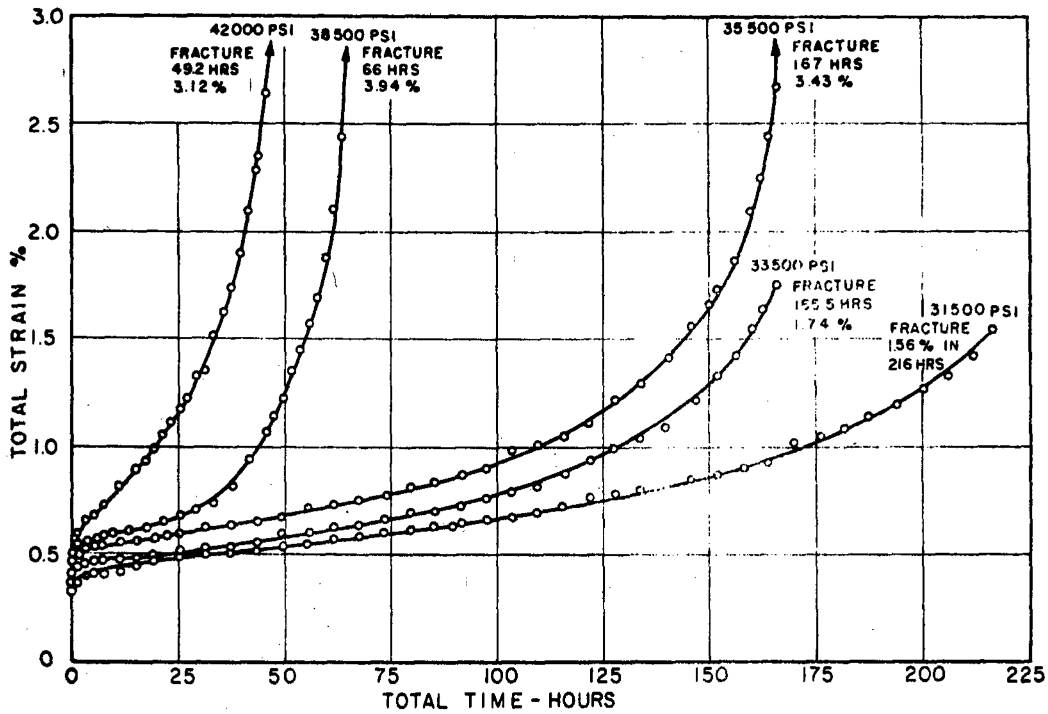


FIG. 8 CREEP OF 75 S-T6 300°F INTERMITTENT LOAD AND TEMPERATURE IN PHASE 1 ½ HR/ ½ HR CYCLE 7

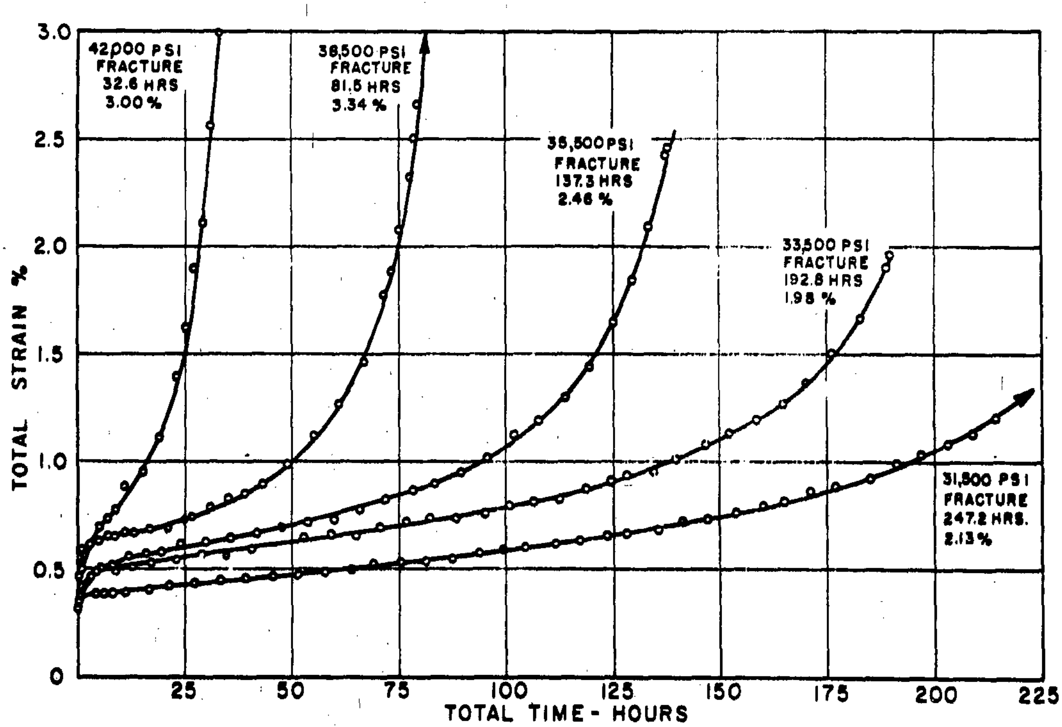


FIG. 9 CREEP OF 75S-T6 300°F INTERMITTENT LOAD AND TEMPERATURE 1½ HR/½ HR OUT OF PHASE CYCLE 8

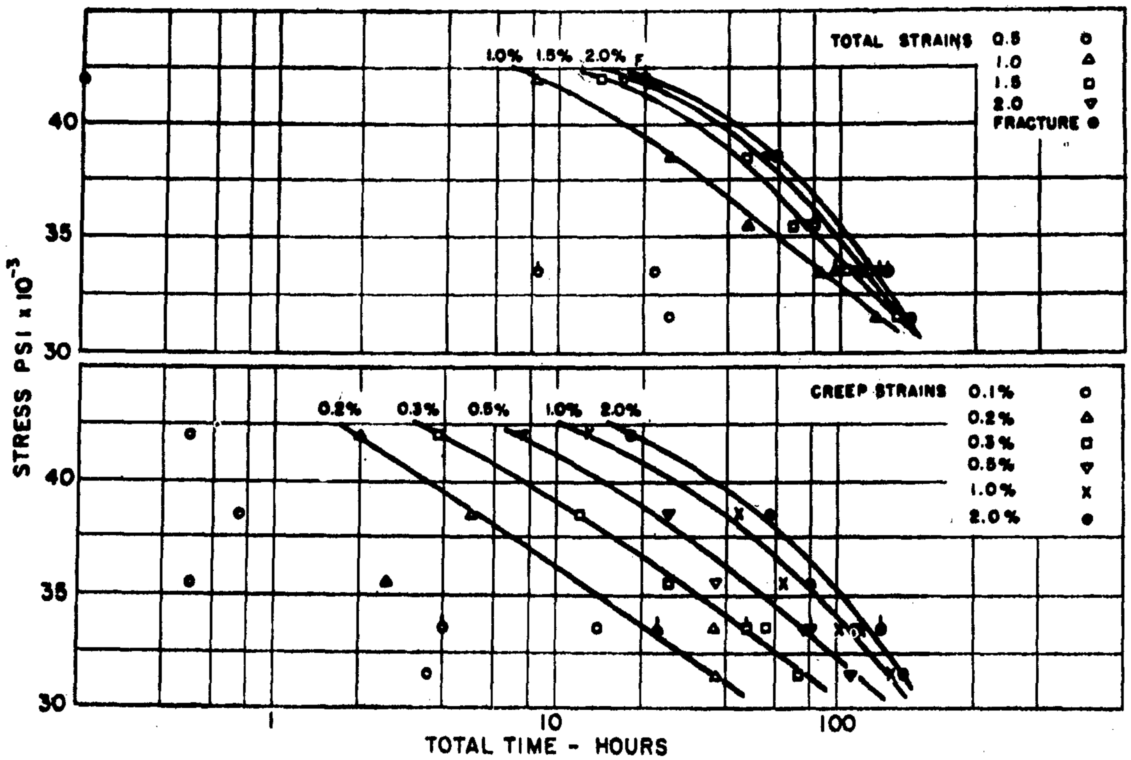


FIG. 10 CREEP OF 75S-T6 300°F STRESS / LOG TIME CURVES
STEADY LOAD AND TEMPERATURE

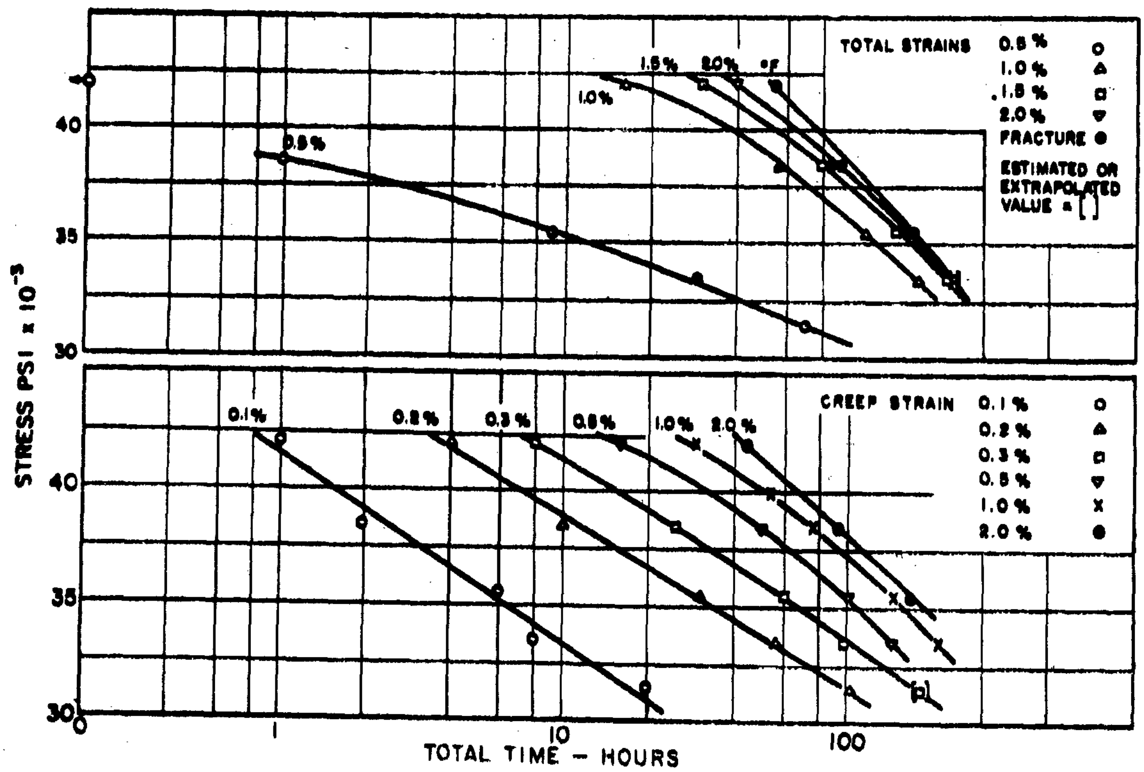


FIG. 11 CREEP OF 75S-T6 300°F STRESS / LOG TIME CURVES
STEADY LOAD INTERMITTENT TEMPERATURE - 1 HR / 1 HR CYCLE 3

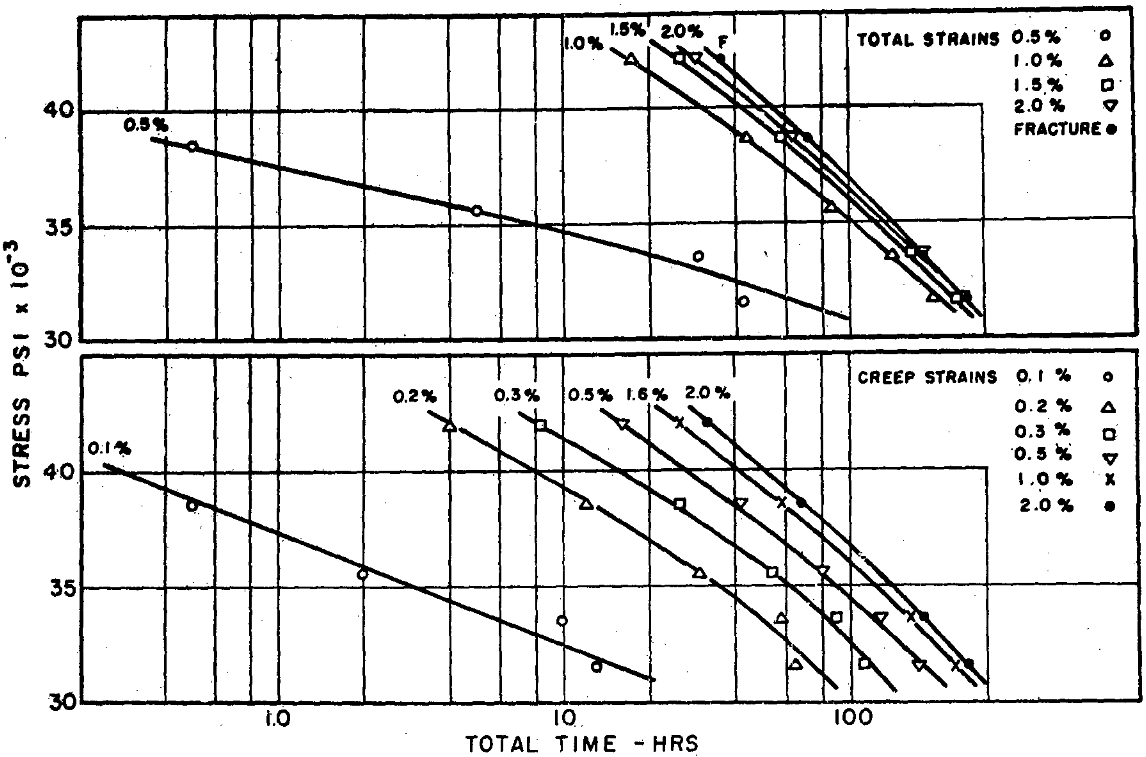


FIG. 12 CREEP OF 75S-T6 300°F STRESS/LOG TIME CURVES
STEADY TEMPERATURE INTERMITTENT LOAD 1HR/1HR CYCLE 1

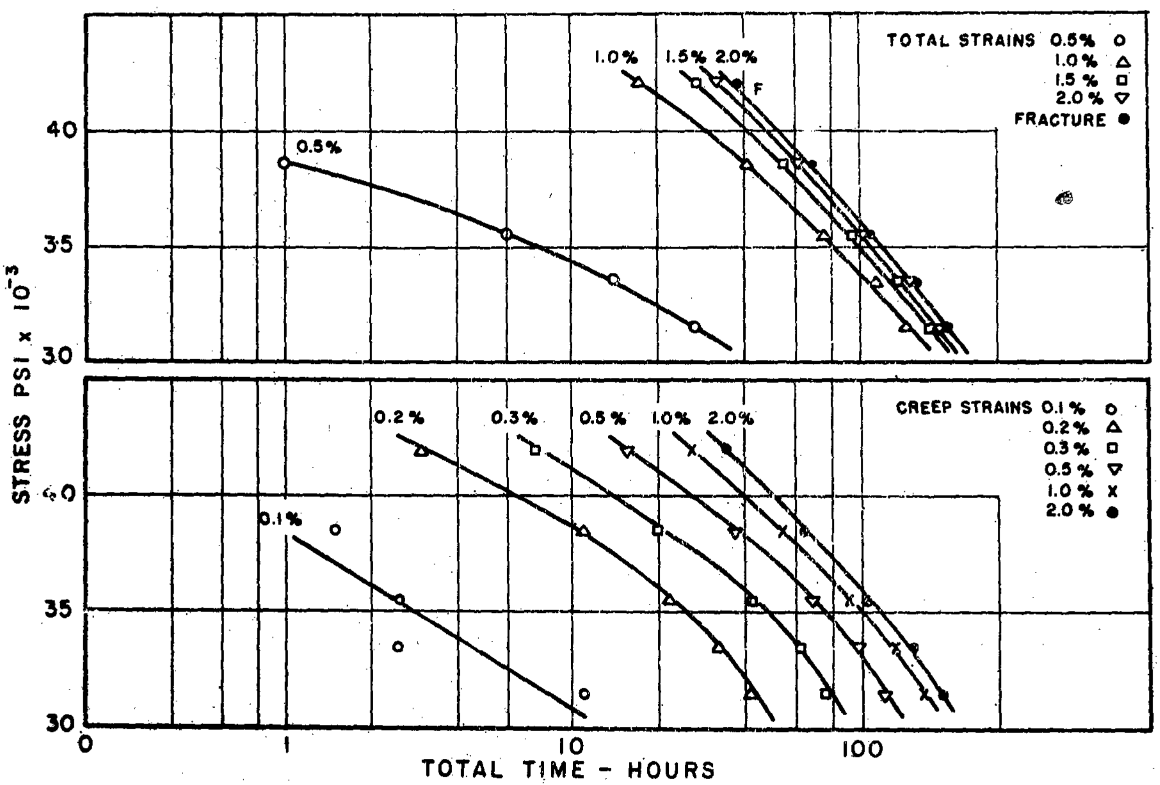


FIG. 13 CREEP OF 75S-T6 300°F STRESS/LOG TIME CURVES
STEADY TEMPERATURE, INTERMITTENT LOAD 1½ HRS./½ HR CYCLE 2

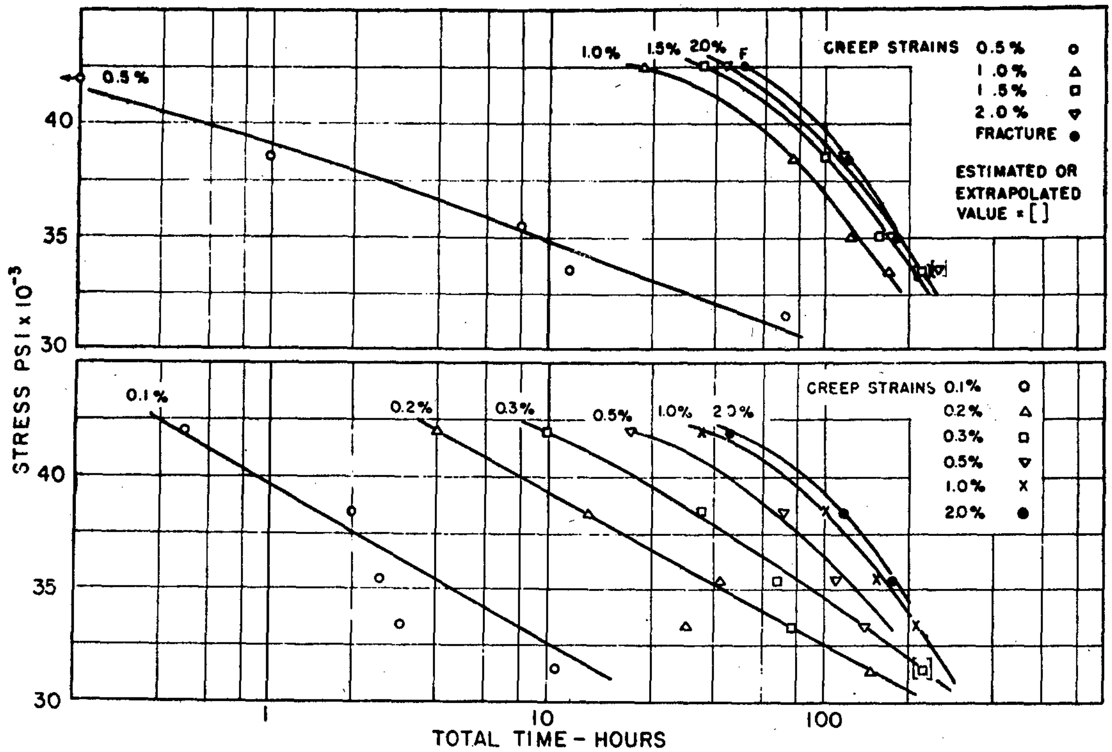


FIG. 14 CREEP OF 75S-T6 300°F STRESS / LOG TIME CURVES
INTERMITTENT LOAD AND TEMPERATURE IN PHASE - 1 HR / 1 HR CYCLE 5

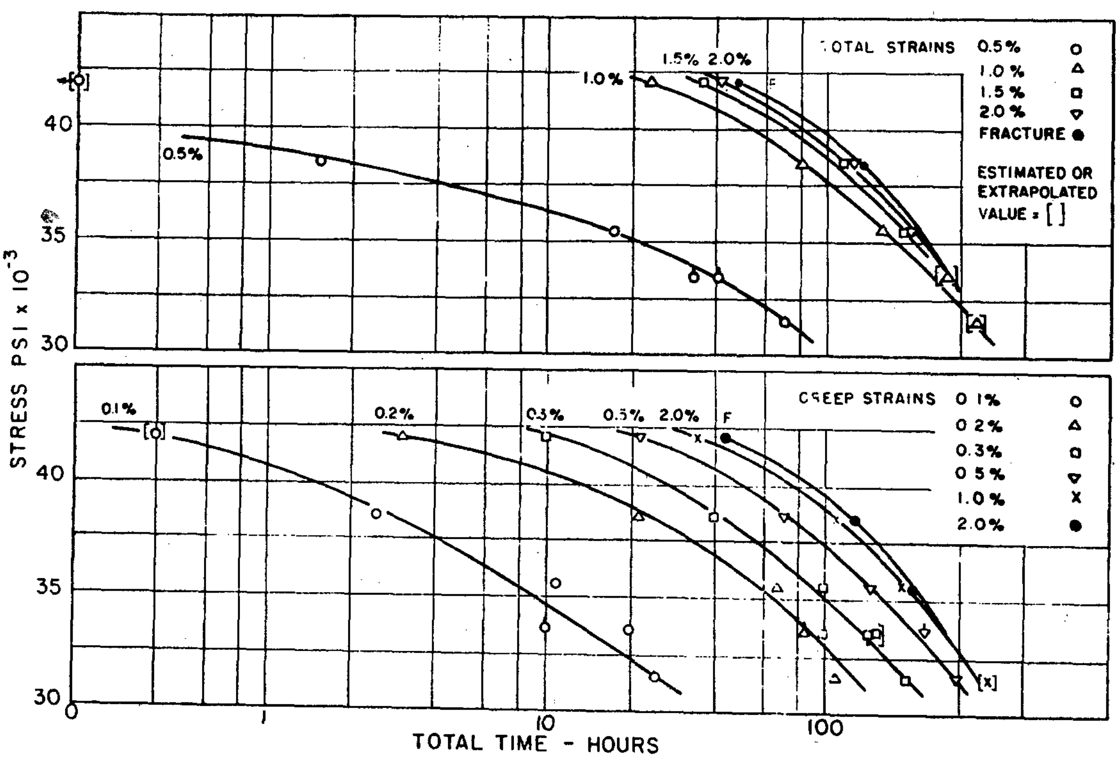


FIG. 15 CREEP OF 75S-T6 300° STRESS / LOG TIME CURVES
INTERMITTENT LOAD AND TEMPERATURE OUT OF PHASE - 1 HR/1 HR CYCLE 6

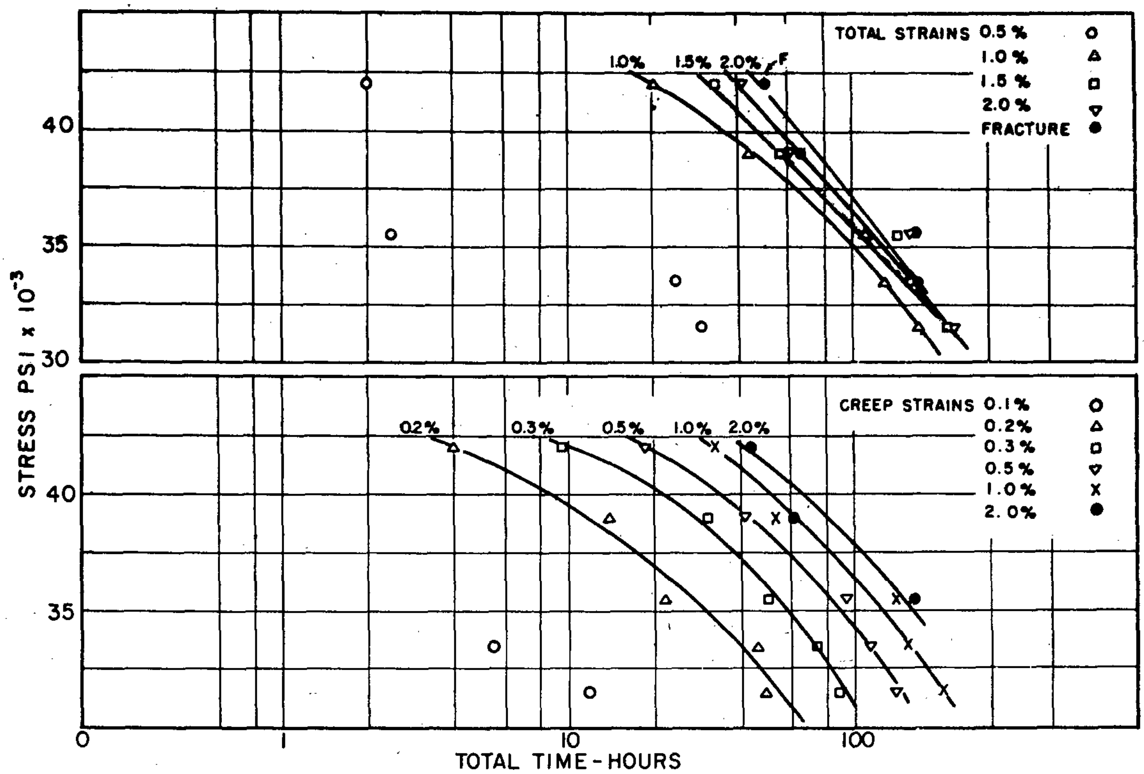


FIG.16 CREEP OF 75S-T6 300° F STRESS / LOG TIME CURVES
INTERMITTENT LOAD AND TEMPERATURE IN PHASE - 1½ HR/½ HR CYCLE 7

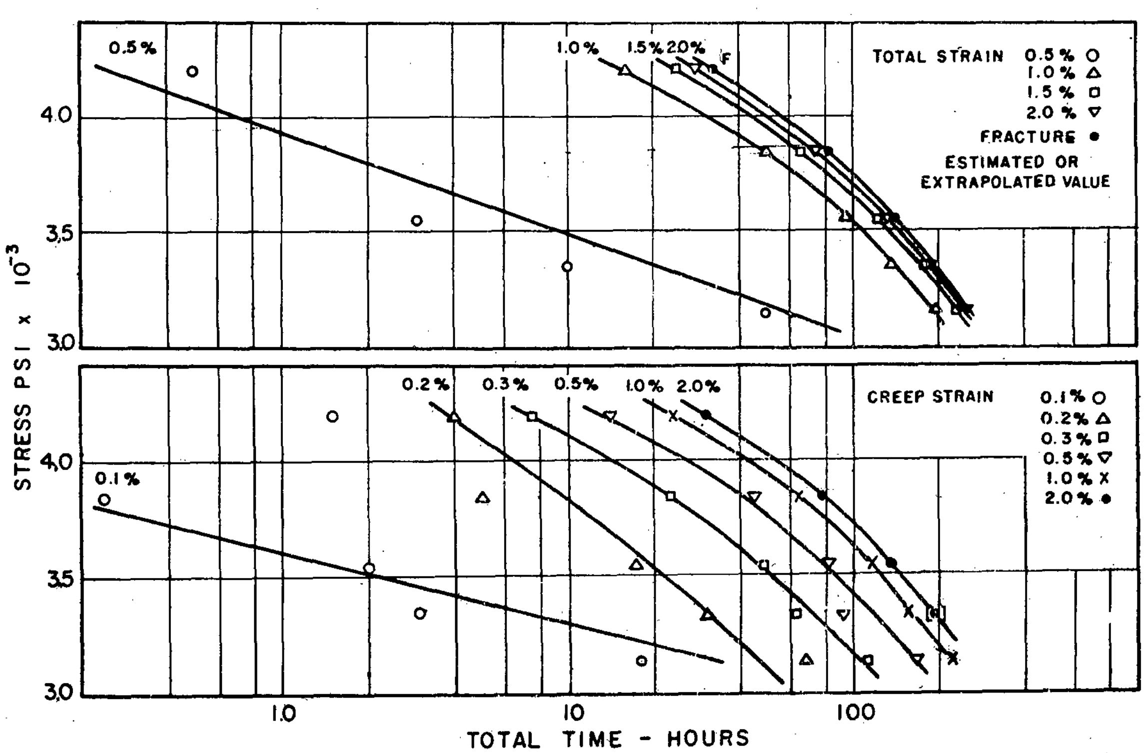


FIG.17 CREEP OF 75S-T6 300°F STRESS/LOG TIME CURVES
INTERMITTENT LOAD AND TEMPERATURE OUT OF PHASE 1½ HRS/½ HR CYCLE 8

2. Results at 450°F.

Only one test condition was employed at 450°F, namely that of steady load intermittent temperature, using a cycle of one hour at the steady elevated test temperature for a total cycle time of two hours (Cycle 3). Previous reports(4,5,6) contain creep data for clad aluminum alloy 75S-T6 at 450°F under the other intermittent conditions employed in the tests at 300°F and also the steady load, intermittent heating conditions of cycle 4. The results obtained in the present tests are reported in the same manner as the data obtained at 300°F in Tables III and IV ~~and Figs~~. 18 and 19.

3. Results at 600°F.

Tests at 600°F on 75S-T6 alloy under isothermal steady load and intermittent load using both a 1 hr./1 hr. (Cycle 1) and a $1\frac{1}{2}$ hr./$\frac{1}{2}$ hr. (Cycle 2) cycle have already been reported.(4) In this report the results of further tests at 600°F using steady load intermittent heating (cycle 3) and both in phase (cycles 5 and 7) and out of phase (cycles 6 and 8) combinations of intermittent heating and loading are given. For comparison purposes, steady load isothermal creep tests at 600°F have also been done and the results included in this section. These results, obtained on specimens from the same sheet of material as for the Series II, Cycle 7 tests at 300°F are in good agreement with earlier tests,(4) and the times to reach specified strains appear to be somewhat higher, particularly at the lower stresses, that might be expected from the other presently reported intermittent data at 600°F, which were obtained using specimens cut from other sheets of the test material stock. The data have again been assembled in a manner similar

TABLE III

Creep of Clad Aluminum Alloy 75S-T6 at 450°F.

Steady Stress, Intermittent Temperature. 1 Hr./1 Hr.

Cycle 3. Total Times to Reach Various Total Strains

Stress psi	Total Times to Reach Total Strains of:							Elong. % on 2" in Fracture
	0.5%	1.0%	1.5%	2.0%	3.0%	5.0%	Fracture	
12,000	9	20	14	25½	--	--	27.8	2.76
10,000	7	15½	19	21½	--	--	22.5	2.12
9,500	35	73	91	100	111	116	116.9	6.03
9,000	48	92	101	122	135	148	158.0	11.4
8,600	55	119	150	166	186	201½	202.5	5.30
8,200	45	158	215	246	--	--	N.F.	--

TABLE IV

Creep of Clad Aluminum Alloy 75S-T6 at 450°F.

Steady Stress, Intermittent Temperature. 1 Hr./1 Hr. Cycle 3.

Total Times to Reach Specified Creep Strains

Stress psi	Total Times to Reach Creep Strains of:					
	0.1%	0.2%	0.3%	0.5%	1.0%	2.0%
12,000	1	3	7	13	22	26
12,000	1½	3	5½	10	16½	22
10,000	3	14	24	40	61	75
9,500	3	16	28	46	76	102
9,000	12	27½	42	62	95	123½
8,600	2	18	36	71	127	168½
8,200	—	1	24	79	171½	250

NOTE: The following mean values of the initial strains on loading were used in arriving at the data of Tables III and IV:

12,000 psi	0.140%
10,000 psi	0.117%
9,500 psi	0.111%
9,000 psi	0.106%
8,600 psi	0.100%
8,200 psi	0.096%

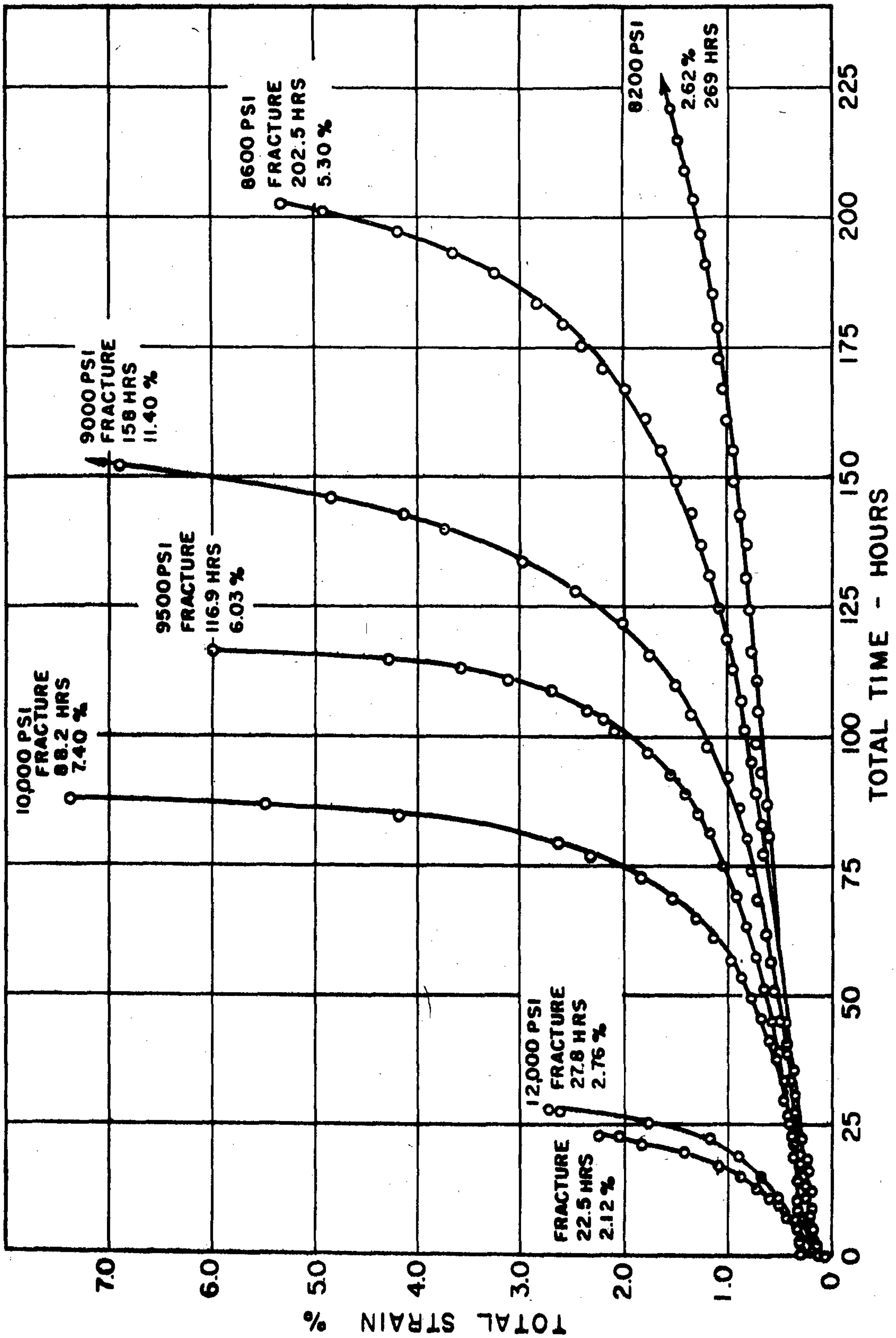


FIG.18 CREEP OF 75S-T6 450° F STEADY LOAD INTERMITTENT TEMPERATURE 1 HR/1HR CYCLE 3

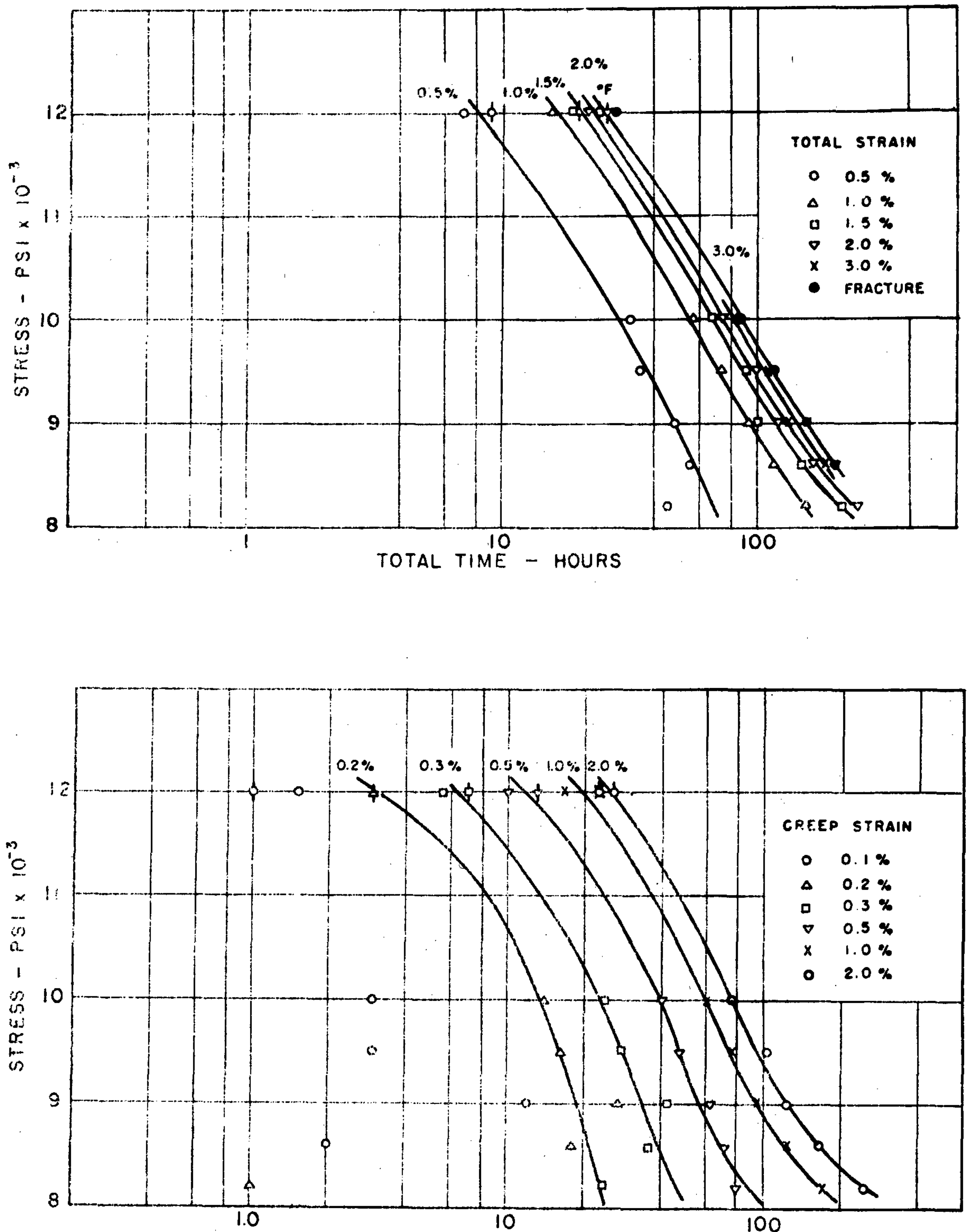


FIG. 19 CREEP OF 75S-T6 450°F STRESS/LOG TIME CURVES STEADY LOAD INTERMITTENT TEMPERATURE 1HR/1HR CYCLE 3

TABLE V

Creep of Clad Aluminum Alloy 75S-T6 at 600°F under Various Intermittent Conditions

Type of Test	Stress psi	Total Time (Hrs.) to Reach Total Strains of:									Elong. % on 2" at Fracture
		0.2%	0.5%	1.0%	1.5%	2.0%	3.0%	5.0%	7.0%	Fracture	
Steady Load and Temperature	5,000	~½	2	4½	7	8½	11½	15	17¼	19.8	13.05
	5,000	~½	2	4	5½	7	9	12	13¾	16.8	22.67
	4,500	--	2½	7	11	15	20	27½	32	40.2	22.83
	4,000	1	6	17	27½	37	51½	73½	87½	103.5	12.09
	3,500	3	16	41	64	87	128	190	229	249.8	9.36
	3,200	7	31	77	118	158	228	[325]	--	N.F.	--
Steady Load Intermittent Temperature 1 Hr./1 Hr. Cycle 3	6,000	--	--	~½	~1	1¼	2	3	4	4.6	15.25
	5,000	½	1½	4	7	9	12½	17¼	20¼	24.4	12.33
	5,000	½	2	5	8	10	14	19	22	26.3	11.54
	4,500	1	5	11½	17½	23	31	43	50	58.6	10.60
	4,000	2	11	26	39	50	69	99	119	134.5	8.90
	3,500	5	29	76	117	161	[230]	[290]	--	N.F.	--
	3,200	4	26	80	132	183	261	[340]	--	N.F.	--
Intermittent Load and Temperature In Phase 1 Hr./1 Hr. Cycle 5	5,000	1	3½	6½	9	11	14	19	21½	22.7	8.47
	4,500	½	7	17½	27	34½	47	63	72½	80.2	9.24
	4,000	1	8½	24	34	53	75½	107	127	138.6	8.49
	3,500	2	22	63	118	174	[275]	--	--	N.F.	--
	3,200	6	47	109	223	--	--	--	--	N.F.	--
Intermittent Load and Temperature Out of Phase 1 Hr./1 Hr. Cycle 6	5,000	--	4	10	15½	20	26	34	38	42.3	10.81
	4,500	½	8	20	29	38	53	75	90	110.2	15.10
	4,200	2	19	46	69	88	120	--	--	152.5	4.39
	4,000	6	32	71	104	138	198	--	--	N.F.	--
	3,500	13	62	144	[246]	--	--	--	--	N.F.	--
	3,200	16	100	[255]	--	--	--	--	--	N.F.	--
Intermittent Load and Temperature In Phase 1½ Hr./½ Hr. Cycle 7	5,000	--	1¾	5	8	11	15	20	22¼	24.8	10.02
	4,500	1	4½	11	17	22	30½	41	47½	54.8	11.86
	4,000	1½	7	19½	33	45½	66	92	108	124.3	10.6
	3,500	2	18	55½	94½	130	199	--	--	N.F.	--
	3,200	6	36	99	163	227	--	--	--	N.F.	--
Intermittent Load and Temperature Out of Phase 1½ Hr./½ Hr. Cycle 8	5,000	--	2½	6	9	11½	15	19½	22¼	26.3	15.50
	4,500	1½	7	14½	21	27	37	48½	55½	62.4	10.43
	4,000	--	5	21	39	54	80	122	150	174.5	9.64
	3,500	3	29	74	120	166	251	--	--	N.F.	--
	3,200	6	38	99	165	[229]	--	--	--	N.F.	--

[ ] = Estimated or Extrapolated Value.

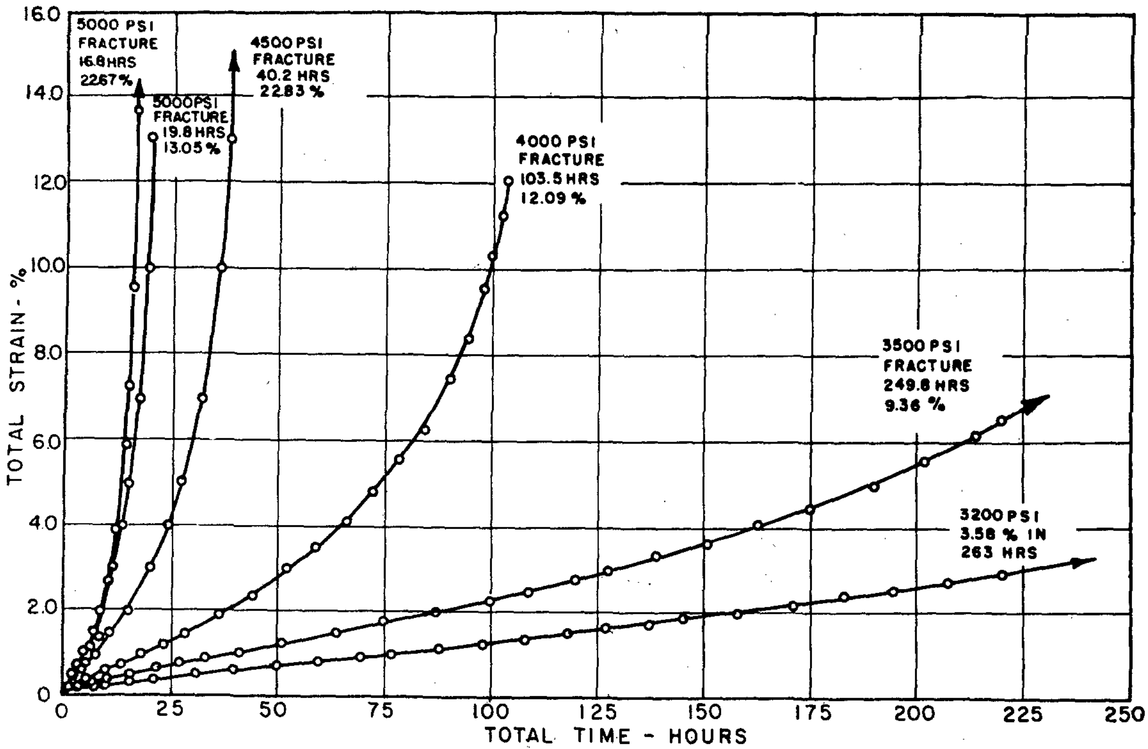


FIG. 20 CREEP OF 75S-T6 600° F STEADY LOAD AND TEMPERATURE

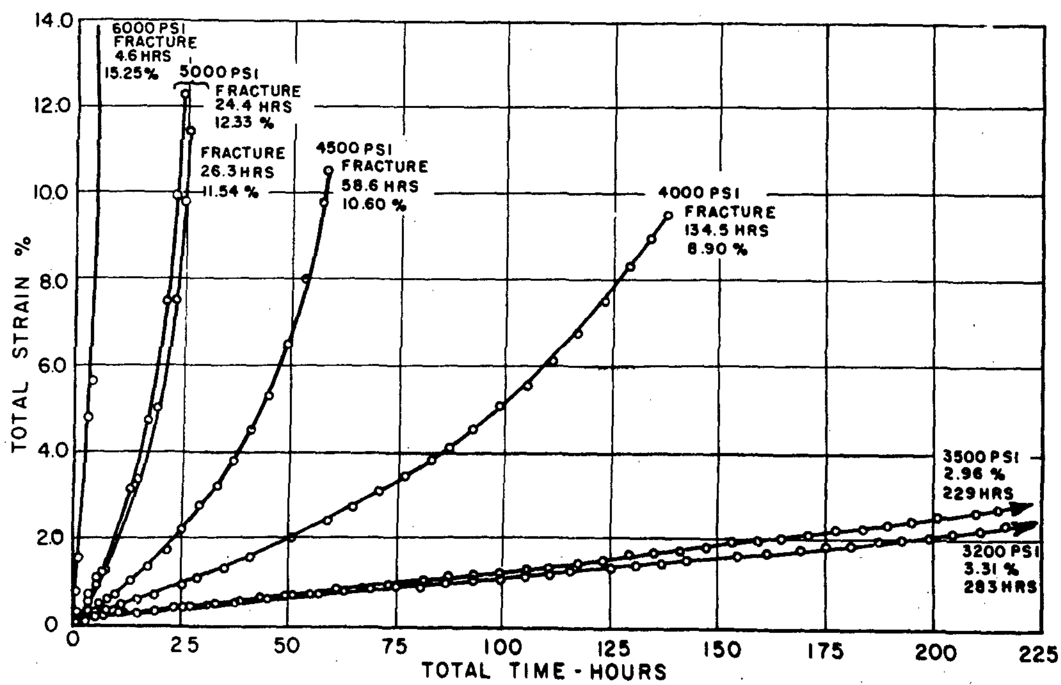


FIG. 21 CREEP OF 75S-T6 600° F STEADY LOAD INTERMITTENT TEMPERATURE 1 HR/1 HR CYCLE 3

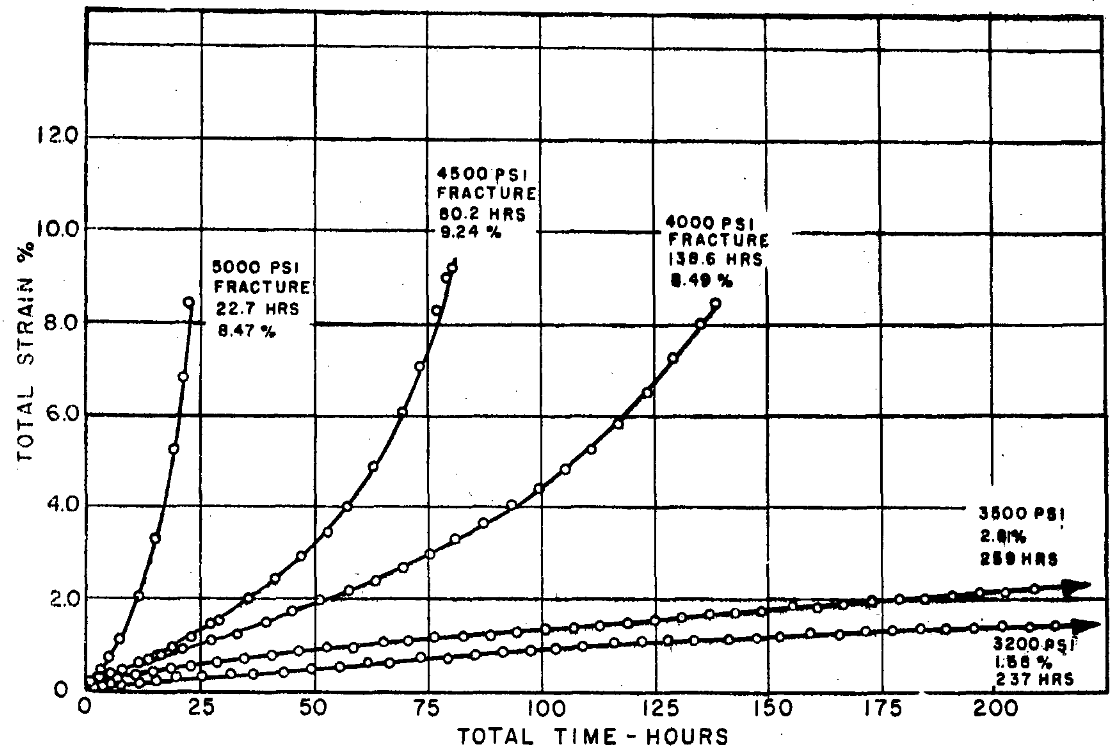


FIG. 22 CREEP OF 75S-T6 600° F INTERMITTENT LOAD AND TEMPERATURE IN PHASE 1 HR/1 HR CYCLE 5

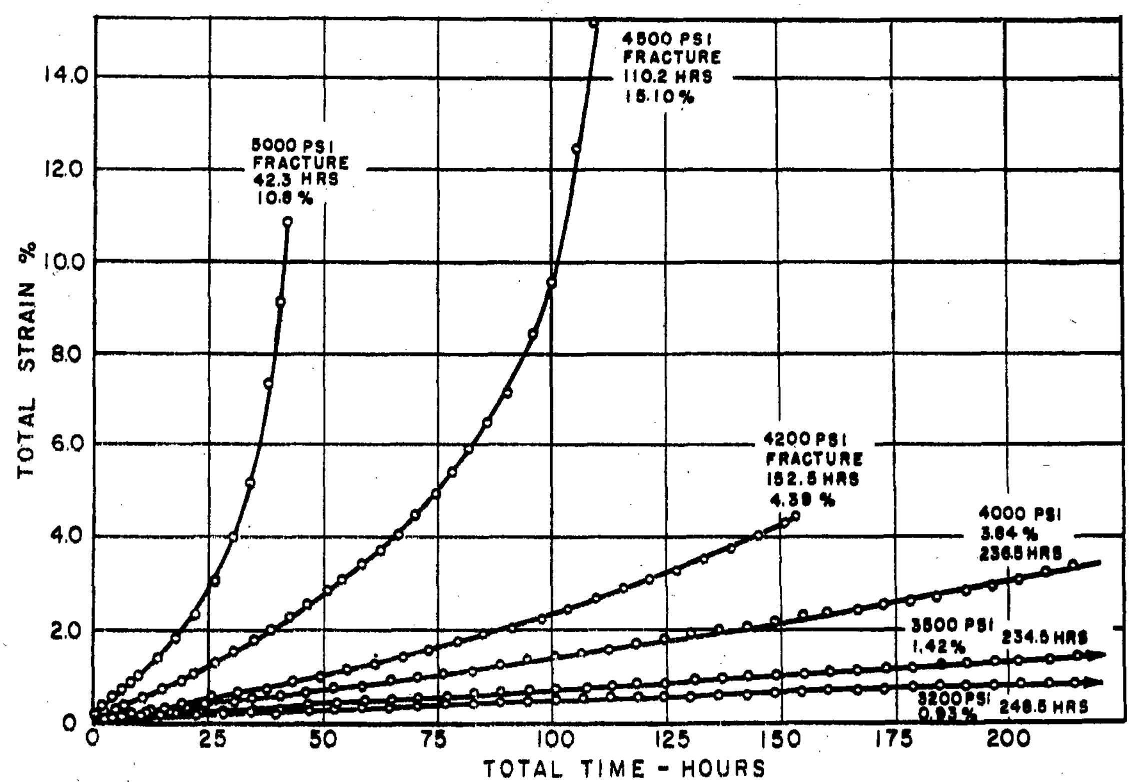


FIG. 23 CREEP OF 75 S-T6 600°F INTERMITTENT LOAD AND TEMPERATURE OUT OF PHASE 1 HR/1 HR CYCLE 6

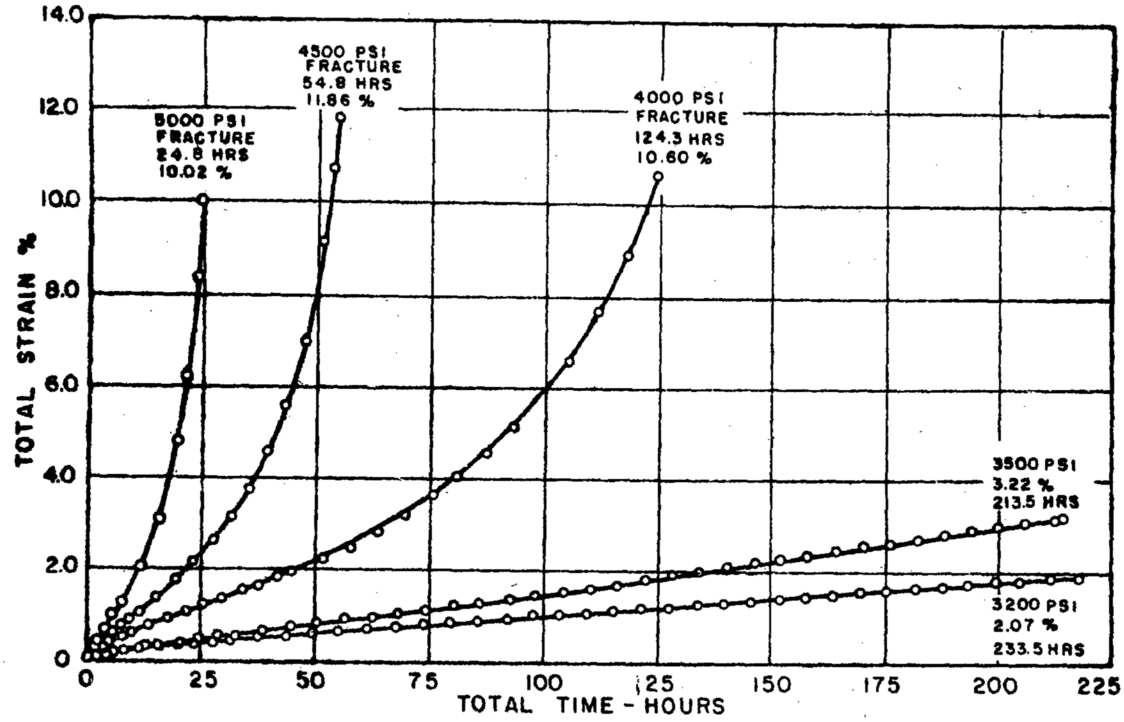


FIG. 24 CREEP OF 75 S-T6 600° F INTERMITTENT LOAD AND TEMPERATURE IN PHASE $1\frac{1}{2}$ HR/$1\frac{1}{2}$ HR. CYCLE 7

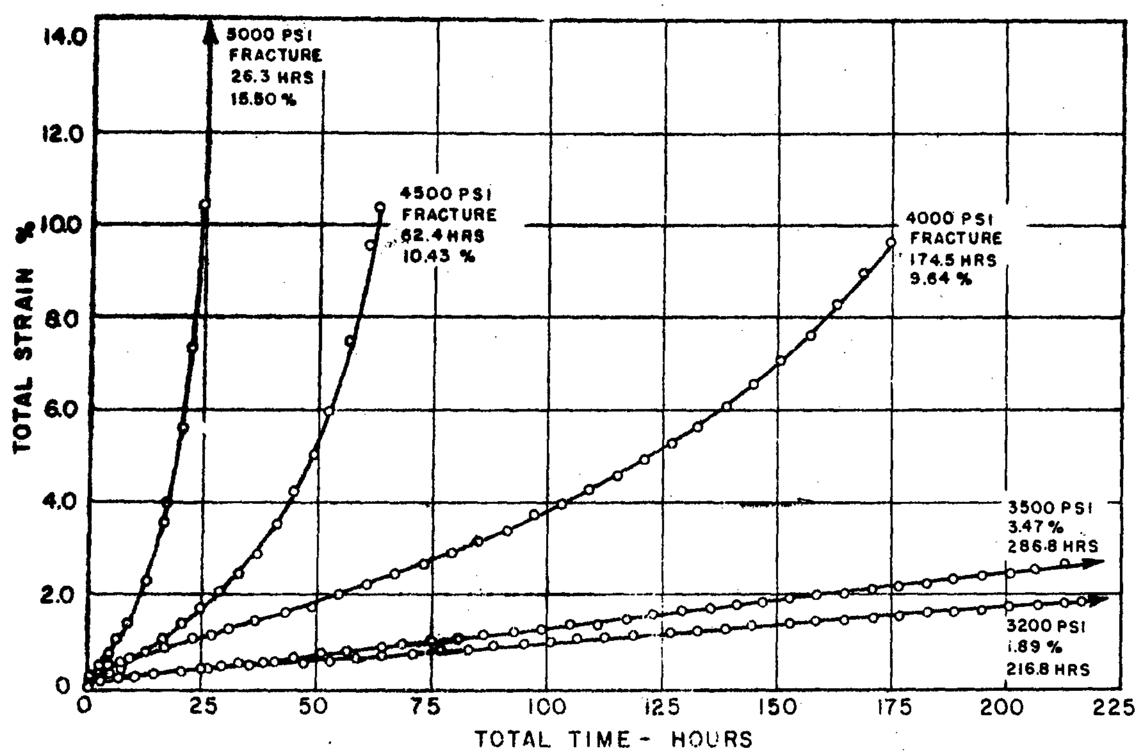


FIG. 25 CREEP OF 75 S-T6 600° F INTERMITTENT LOAD AND TEMPERATURE OUT OF PHASE $1\frac{1}{2}$ HR/$\frac{1}{2}$ HR CYCLE 8

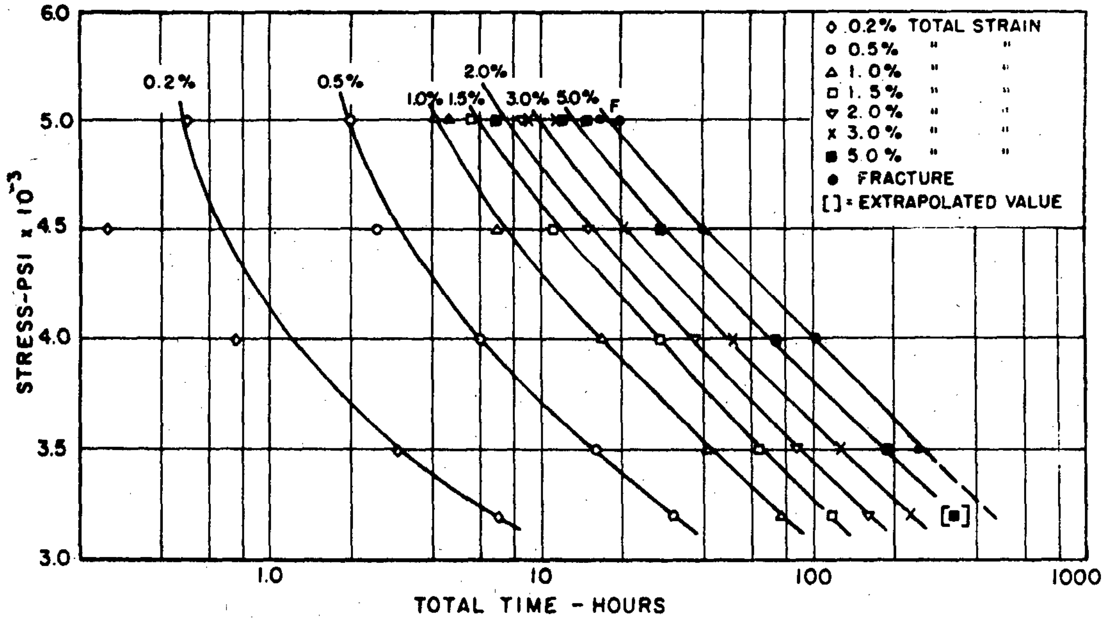


FIG. 26 CREEP OF 75S-T6 600°F STRESS/LOG TIME CURVES
STEADY LOAD AND TEMPERATURE

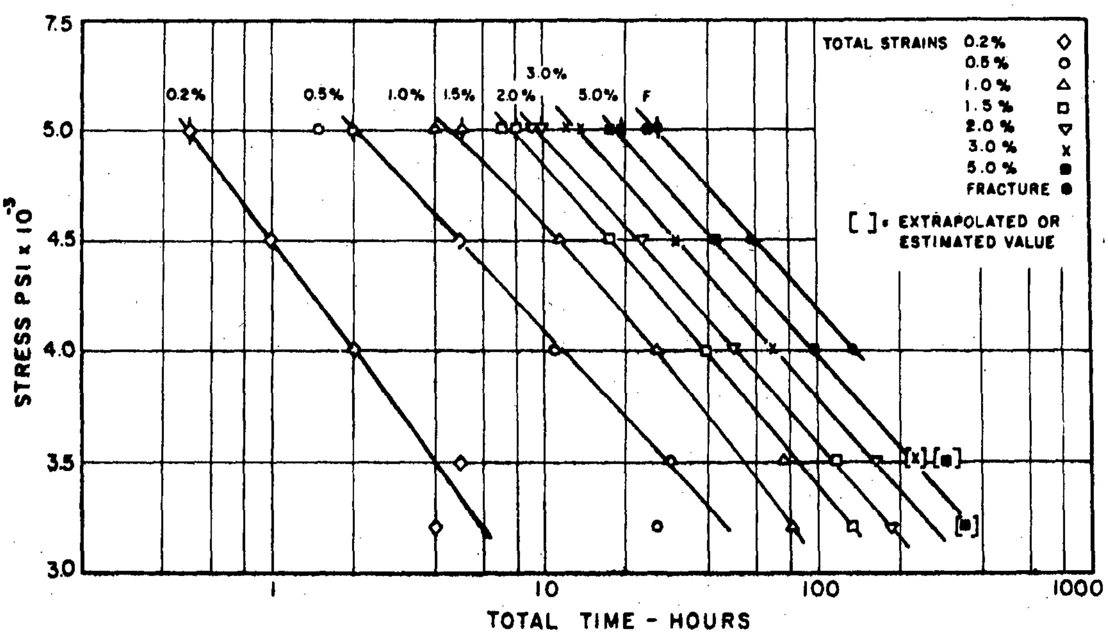


FIG. 27 CREEP OF 75S-T6 600°F STRESS/LOG TIME CURVES
STEADY LOAD AND INTERMITTENT TEMPERATURE 1 HR/1 HR CYCLE 3

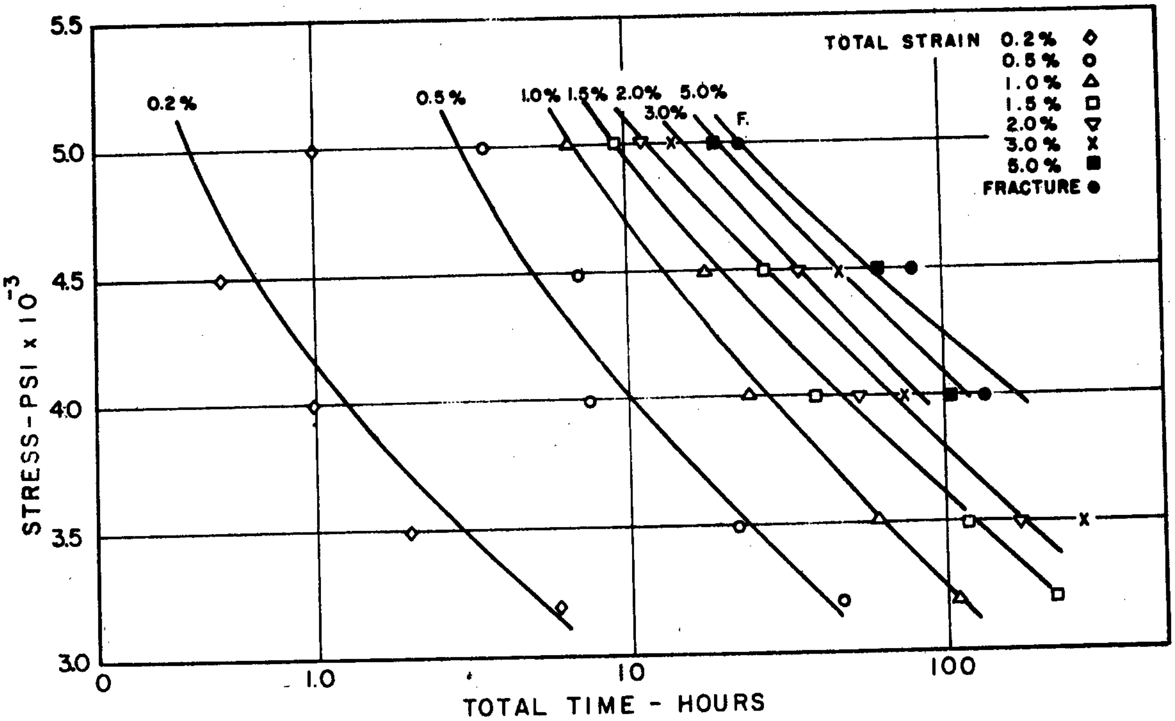


FIG. 28 CREEP OF 75S-T6 600°F STRESS/LOG TIME CURVES
INTERMITTENT LOAD AND TEMPERATURE IN PHASE 1 HR/1 HR CYCLE 5

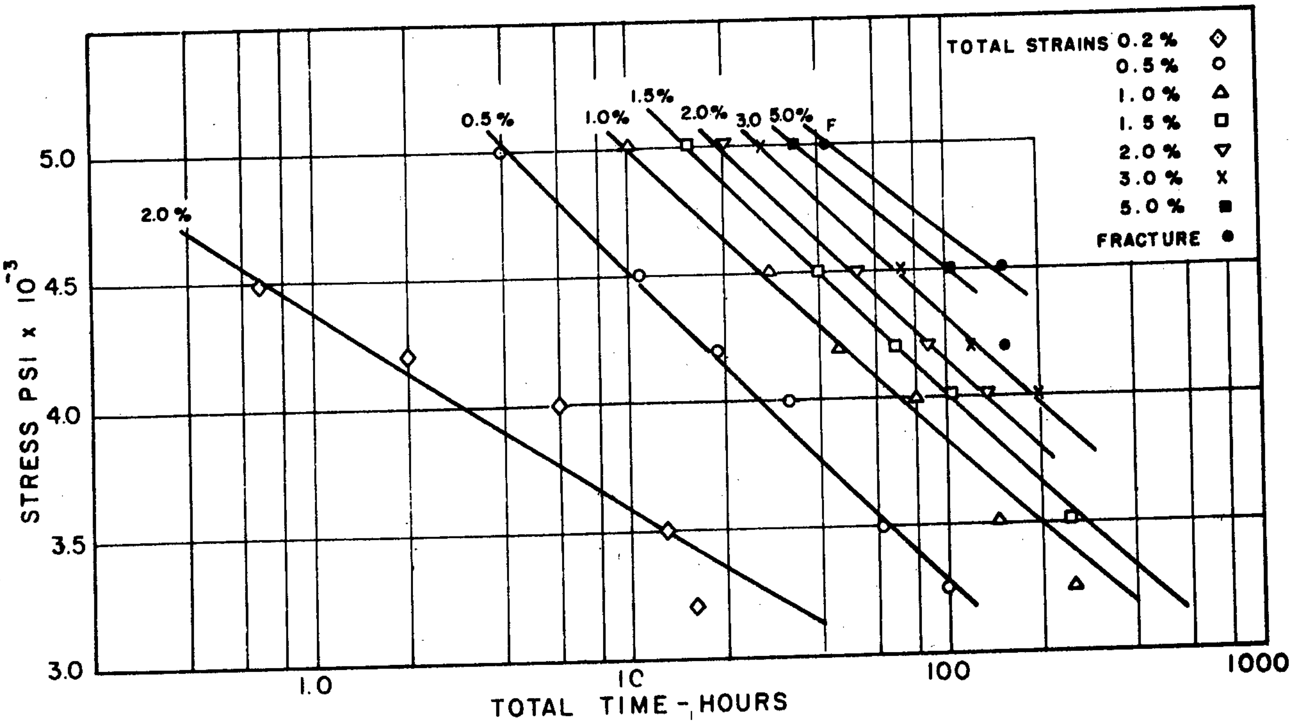


FIG. 29 CREEP OF 75S-T6 600° F. STRESS/LOG TIME CURVES
INTERMITTENT LOAD AND TEMPERATURE
OUT OF PHASE 1 HR/1 HR CYCLE 6

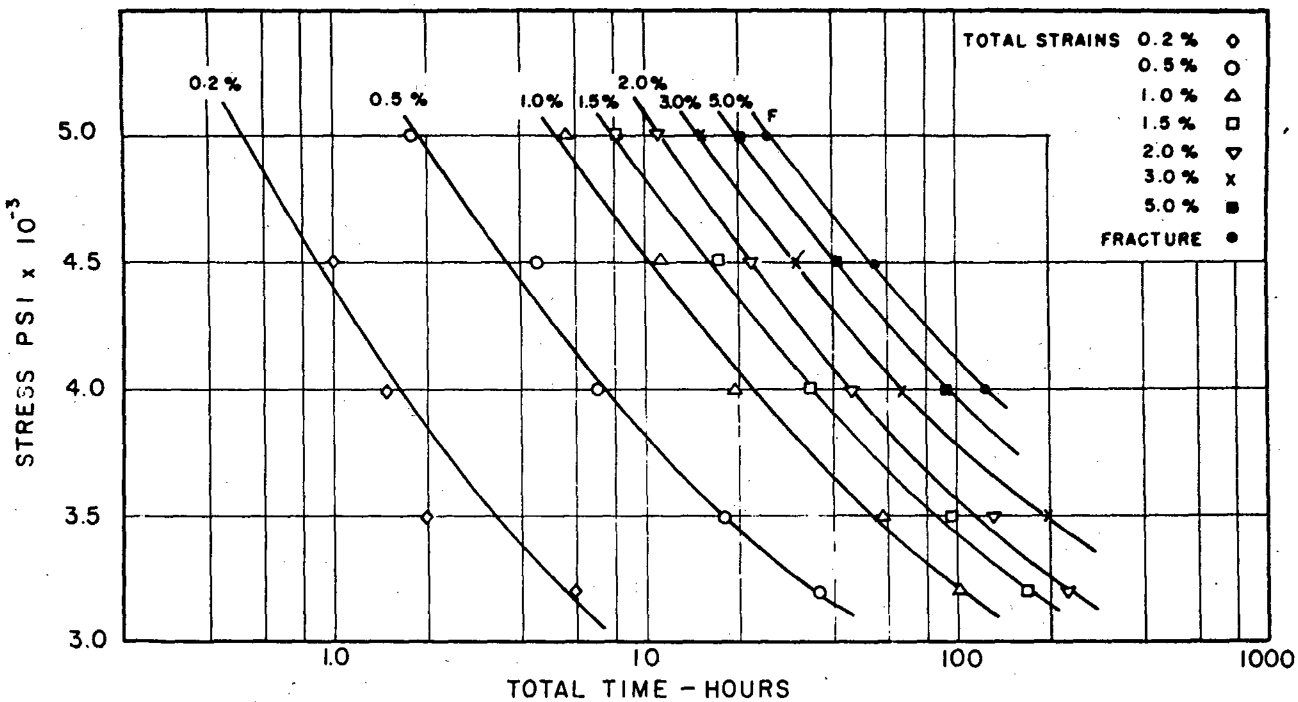


FIG. 30 CREEP OF 75 S-T6 600° F STRESS / LOG TIME CURVES
INTERMITTENT LOAD AND TEMPERATURE $1\frac{1}{2}$ HRS/ $\frac{1}{2}$ HR
IN PHASE CYCLE 7

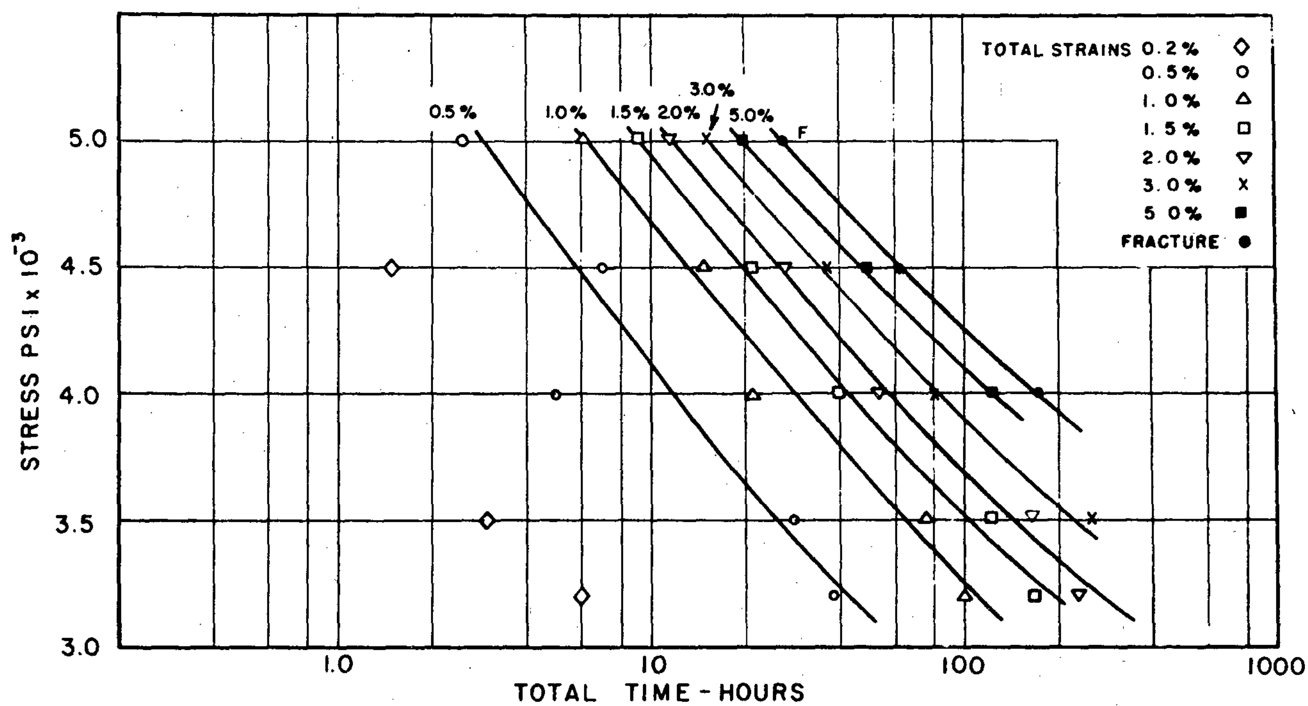


FIG. 31 CREEP OF 75 S-T6 600° F STRESS/LOG TIME CURVES
INTERMITTENT LOAD AND TEMPERATURE
OUT OF PHASE $1\frac{1}{2}$ HR/$\frac{1}{2}$ HR CYCLE 8

to that used for the test results at 300°F and 450°F, with the exception that the use of creep strains has not been continued. At the highest stress of 5,000 psi the strain on initial application of the load is estimated to be 0.09%, while at the lowest stress of 3,200 psi the corresponding initial strain is 0.06%. Not only is the accuracy in the estimation of these very small strains somewhat low, but even at the lowest stress the time taken to reach 0.5% creep strain is not significantly different from that taken to reach 0.5% total strain. It has therefore been considered sufficient to report only the times to reach specified total strains, data for 0.2% total strain being included to provide an indication of the creep behavior of the material at small deformations, even though these data are on occasions somewhat erratic.

Figs. 20-25 inclusive show the creep curves obtained under the various test conditions employed, while the results are summarized as the total elapsed times taken to reach specified total strains in Table V. The values from this table have been plotted as stress/log time design curves in Figs. 26-31 inclusive.

DISCUSSION OF TEST RESULTS

1. Methods of Analytical Approach

With the completion of the present test program, a fairly extensive set of data at the three temperatures, 300°F, 450°F, and 600°F, on 75S-T6 alloy was made available for detailed analysis. Four methods of analyzing these data have been used, and on the basis of present results one has been selected as the most satisfactory. Method 1 was based on the use of the total times (t_{ex}) to reach various total strains as read directly from plots of total strain against total time. Method 2 was similar, but various creep strains were used in place of total strain values. The creep strains are determined by subtracting from the total strains measured by the equipment all plastic and elastic strains occurring on the initial application of the test load. For 75S-T6 at the test temperatures, these initial strains included very little, if any, plastic deformation, even at the highest test load of 42,000 psi at 300°F when the initial strain was 0.45%. In method 3 the experimental data were plotted on stress versus log time coordinates as the total elapsed time at the various test stresses to reach specified values of the total strain (0.5%, 1.0%, 1.5%, 2.0% etc.) and rupture. Smooth average curves were then drawn for each specified strain, and the times to reach these strains at any given stress can then be read from the curves. For the test stresses, these times, (t_g) may be considered as the most probable times required to reach the specified strains. In this way the effects of the scatter normally encountered in creep testing were minimized without an excessive burden of testing, and by replotting the t_g values at various strains for each test stress on strain/time coordinates a typical creep curve for each test stress may be obtained. Creep curves at any intermediate stress can obviously also be arrived at by interpolation, while limited extrapolation can also be carried out in many cases if due judgment is exercised. Method 4 involves a similar approach, using creep strains instead of total strains.

Two different view points have been used in the analyses of the data. In the first, comparisons of the experimental results under the various cyclic conditions have been made on a basis of net time under load at the test temperature, in order to assess the effect of cyclic conditions on the rate at which creep takes place under the influence of the test stresses and temperatures.

A second type of analysis has been carried out using the correlation and prediction methods, previously discussed,[4,5,6] based on the proposed functional equation

$$\varepsilon = F\left\{t f(\sigma)\right\} \qquad (1)$$

where ε = total strain

t = time

σ = stress

F = strain function

f = stress function.

Whence

$$\frac{{}_{\varepsilon_1}t_s}{{}_{\varepsilon_1}t_\sigma} = K = \frac{{}_{\varepsilon_2}t_s}{{}_{\varepsilon_2}t_\sigma} \qquad (5)$$

if the function f is independent of strain, where

${}_{\varepsilon_1}t_s$ = time at some standard stress to reach a total strain ε_1

${}_{\varepsilon_1}t_\sigma$ = time at some other stress, σ , to reach a total strain ε_1

${}_{\varepsilon_2}t_s$ = time at some standard stress to reach a total strain ε_2

${}_{\varepsilon_2}t_\sigma$ = time at the other stress, σ , to reach a total strain ε_2

In the following discussion, the constant K as calculated using the experimentally determined times, t_{ex}, is denoted as K_{ex} , while that calculated using the most probable times, t_g , obtained from the appropriate stress/log time curves is denoted by K_g . Correspondingly, the predicted times, calculated by using t_{ex} for the chosen standard test and the appropriate K_{ex} in accordance with equation (5), will be designated "calc.t_{ex}", while the calculated times, using t_g and the appropriate K_g will be designated "calc. t_g". For the intermittent conditions, a second calculated time may be arrived at by using t_g for the standard stress under intermittent conditions, and K_g for the steady load and temperature condition at the appropriate stress. This calculated time, designated "calc. $\bar{t}_g$", is the essential objective of the prediction attempted with the suggested method of analysis. For its calculation, only a representative test at the single standard stress under the intermittent condition is required in addition to the normal isothermal, steady load creep data.

2. Analysis of 300°F Data

(a) Net Time Approach

The results obtained by comparing the isothermal steady load data, and the seven sets of various cyclic condition data on a net time basis are summarized in Table VI. Inspection of these results suggests that the effect of the various types of cycles on the creep behavior of 75S-T6 alloy at 300°F divides them into two main groups. In the first group lie those conditions which have little or no effect on the creep resistance of the material. The in-phase combined load and temperature cycles 5 and 7 can be classed with the steady load isothermal condition, although there are indications that rupture may be slightly delayed by the intermittent condition. The steady load intermittent temperature conditions of Cycle 3 may also be classed with the first group, since although the net times to specified strains and fracture are slightly below the average for the first group, the differences are hardly enough to be considered significant. The explanation of the above grouping is apparent when the effect of temperature on steady load isothermal creep is considered. During the part of the cycles when the test specimen is at room temperature,

TABLE VI

Comparison of Average Net Times (Net t_a) to Reach Specified Strains for Various Intermittent Conditions

Creep of 75S-T6 at 300°F

Stress psi	Total Strain %	Steady Load and Temp.	Cycle 1	Cycle 2	Cycle 3	Cycle 5	Cycle 6	Cycle 7*	Cycle 8
42,000	0.5	--	--	--	--	--	--	--	--
	1.0	8.3	8¾	16	8	11	6	15	8
	1.5	14	13	21	15	18	9	23	12
	2.0	18	15	24	19½	21½	10	30	14
	Fracture	20½	18	27	27	25½	12	36	16
38,500	0.5	< 1	¼	1¼	½	¾	< ½	1½	[1½]
	1.0	25	23	32	27½	37½	20	37½	24
	1.5	42	39½	42	39	50	26	45	33
	2.0	51	33	46	44	55	29	52	37
	Fracture	58	36½	51	47	58½	33	61	40
35,500	0.5	[2]	2¾	4½	5	3½	4	[6]	[5]
	1.0	52	45½	55½	56½	60	40	67	49
	1.5	75	55	69	74	78	46	78	60
	2.0	90	60	76	81	85	50	86	65
	Fracture	97	64½	82½	85	92	51	94	70
33,500	0.5	[10]	10	10	14½	10	9½	[13]	[10]
	1.0	84	65	81	85	85	60	95	75
	1.5	110	81	97	108	110	[65]	112	85
	2.0	122	88	105	113	120	--	120	90
	Fracture	130	91½	112½	[115]	[122]	--	127	91
31,500	0.5	[50]	32	21	35	27	17	[30]	--
	1.0	135	106	112½	[128]	[110]	[84]	126	95
	1.5	155	120	131	[148]	[145]	--	161	115
	2.0	165	126	141	[155]	[160]	--	165	120
	Fracture	170	130	150	--	--	--	--	124

[ ] = Estimated Value

* Series I Data

or considerably below 300°F, creep will be negligible for cycle 3, and cannot occur in cycles 5 and 7 when the load is also removed. Further, except for the brief period near test temperature during the heating portion of each cycle, the specimen will not be affected by such temperature dependent processes as recovery, relaxation, or aging.

Under the out of phase combined intermittent conditions of cycles 6 and 8, and the intermittent stress steady temperature conditions of cycles 1 and 2, the material creeps appreciably faster than under the steady load isothermal condition as judged on a net time basis, with the effect being least in the case of cycle 2. This can be attributed primarily to the recovery and overaging occurring at the elevated temperature in the absence of load. However, this does not appear to be a complete explanation, since on this basis the recovery and overaging effect should be greatest for the case of cycle 1, where the specimen is at temperature in the absence of load for half of the total cycle, and approximately the same for the other three cases, where the specimen is at temperature in the absence of load for ½ hr. in each 2 hr. cycle. In fact cycle 6 appears to be most deleterious, and cycle 2 causes only a slight acceleration of creep. It should be mentioned that in the case of both cycles 1 and 2, creep recovery was observed during the off load portion of the cycle. Although such observations were not possible in the other cases with the equipment used, since thermal effects in the extensometer during the overlapping intermittent temperature part of the combined intermittent cycle obscured the true changes in specimen deformation, it is nevertheless reasonable to assume that creep recovery also took place.

If, during the elevated temperature loaded part of each cycle the creep rate decreases with time, it may happen that in 1½ hrs. of these conditions (cycle 2) the specimen creeps only a little more than in 1 hour (cycle 1). When the specimen is at temperature in the absence of load, the amount of creep recovery in $\frac{1}{2}$ hr. (cycle 2) may not be much less than in 1 hr. (cycle 1). Thus the net deformation during one complete 2 hour cycle of cycle 2 may be but little greater than during one complete 2 hour cycle of cycle 1. On the other hand, the net time taken for this deformation is $1\frac{1}{2}$ hours in the first case (cycle 2), but only 1 hour in the second case (cycle 1). Consequently, if this type of behavior continues in a greater or lesser degree throughout the test, in order to reach a specified strain the net time (at temperature under load) would be greater in the case of cycle 2, or, in general, would be greater the greater the proportion of each cycle which the test specimen spends under load. Fig. 32 shows diagrammatically a hypothetical case under the various cyclic conditions used in second group of cycles, namely those which produce an acceleration of creep and rupture, and it will be seen that while no numerical significance can be attached to the values, the arrangement of the various cycles in order of their relative effect on creep behavior agrees with the experimental observations. A detailed, accurate analysis of the creep behavior during a cycle at various places along the creep curve would obviously be necessary before this hypothesis could be considered further.

(b) Analytical Correlation and Prediction

Although a detailed presentation of the results of applying Eqs. (3) and (4) to the data obtained at 300°F is not possible within the scope of this report, a typical example is given in Table VII for the case of cycle 3 conditions. It will be seen that the predicted values of the time to reach given total strains, agree reasonably well with the values

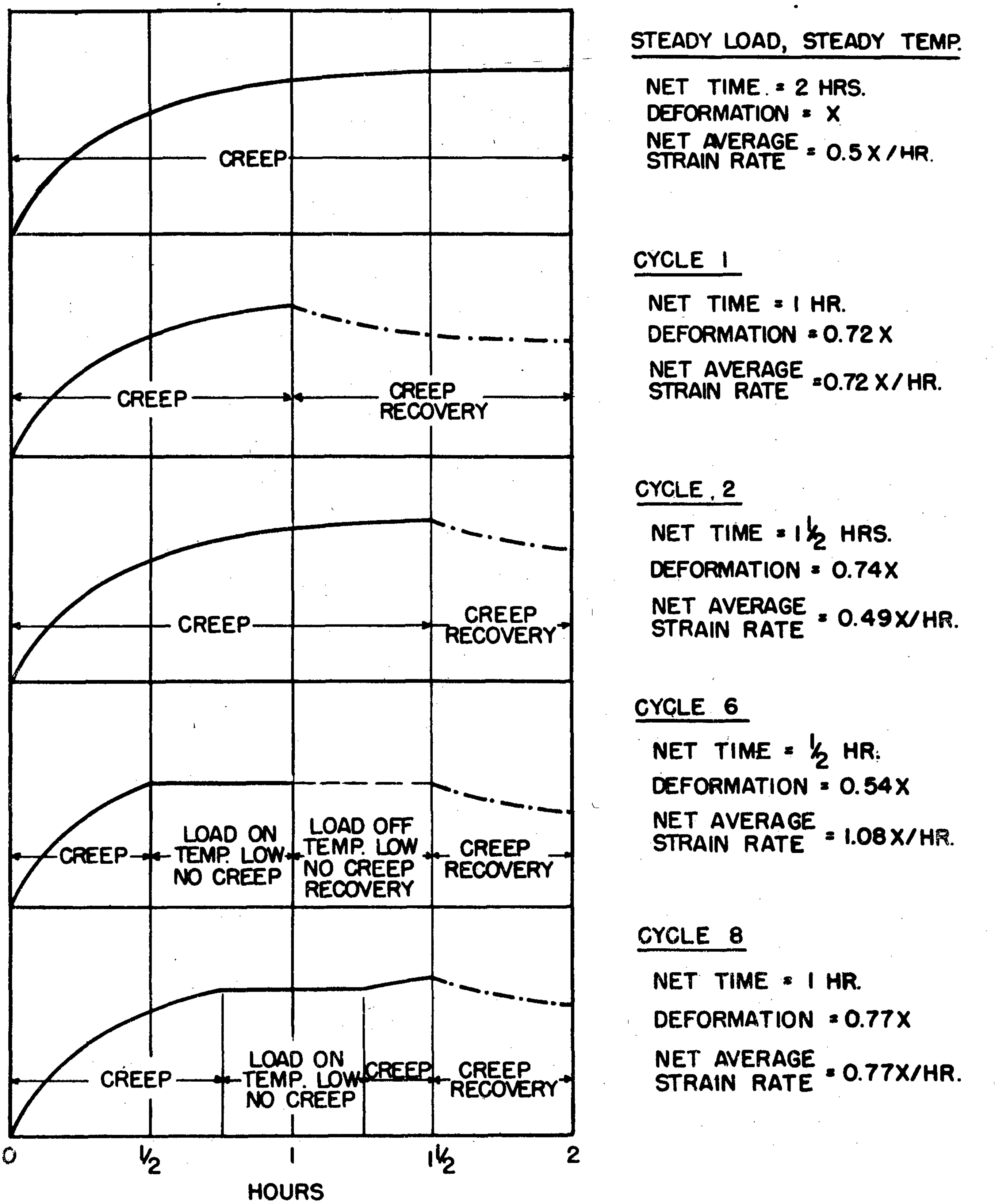


FIG. 32 HYPOTHETICAL DEFORMATION DURING VARIOUS TYPES OF CYCLES.

TABLE VII

Analysis of Creep Data for 75S-T6 at 300°F. Cycle 3

Table VIIa. Total Strain Basis

Stress psi	Variable	Total Times to Total Strains of:					Average (Graphical) "K" Value
		0.5	1.0	1.5	2.0	Fracture	
42,000	t_{ex}	0.1	16.0	30.0	39.	54.4	
	K_{ex}	10.0	3.5	2.6	2.3	1.7	2.6
	calc. t_{ex}	0.4	21.5	30.5	34.0	36.0	
	t_g	—	16.0	30.0	39.0	54.0	
	K_g	--	3.4	2.6	2.3	1.7	2.6
	calc. $\underline{t}_g$	0.4	21.0	30.0	34.0	36.0	
	calc. $\bar{t}_g$	0.3	19.0	27.0	30.0	32.5	
38,500 (Standard)	t_{ex}	1.0	56.0	79.9	88.5	94.0	1.0
	t_g	1.0	55.0	78.0	88.0	94.0	1.0
35,500	t_{ex}	9.0	113.0	145.0	160.0	168.3	
	K_{ex}	0.11	0.50	0.55	0.55	0.56	0.52
	calc. t_{ex}	2.0	108.0	152.0	170.0	181.0	
	t_g	10.0	113.0	148.0	162.0	170.0	
	K_g	0.10	0.49	0.53	0.54	0.55	0.52
	calc. t_g	2.0	106.0	150.0	169.0	181.0	
	calc. $\bar{t}_g$	2.0	98.0	134.0	157.0	168.0	
33,500	t_{ex}	29.0	176.0	219.0	230.0	—	
	K_{ex}	0.035	0.32	0.36	0.39	—	0.34
	calc. t_{ex}	3.0	165.0	232.0	260.0	276.0	
	t_g	29.0	170.0	215.0	225.0	230.0	
	K_g	0.035	0.32	0.36	0.39	0.41	0.36
	calc. t_g	3.0	153.0	217.0	244.0	261.0	
	calc. $\bar{t}_g$	2.5	138.0	195.0	220.0	235.0	
31,500	t_{ex}	70.0	--	--	--	—	
	K_{ex}	0.014	—	—	--	—	0.22
	calc. t_{ex}	4.5	256.0	361.0	404.0	430.0	
	t_g	70.0	255.0	295.0	310.0	--	
	K_g	0.014	0.22	0.26	0.28	--	0.26
	calc. t_g	4.0	211.0	300.0	338.0	361.0	
	calc. $\bar{t}_g$	3.5	183.0	260.0	293.0	313.0	

Table VIIb. Creep Strain Basis

Stress psi	Variable	Total Times to Creep Strain of:						Average (Graphical) "K" Value
		0.1	0.2	0.3	0.5	1.0	2.0	
42,000	t_{ex}	1.0	4.0	8.0	15.5	29.0	44.5	
	K_{ex}	2.0	2.5	3.1	3.2	2.6	2.1	2.6
	calc. t_{ex}	1.0	4.0	9.0	19.0	29.0	36.0	
	t_g	0.9	4.0	8.0	15.5	29.0	44.0	
	K_g	2.7	3.0	3.0	3.0	2.6	2.1	2.7
	calc. t_g	0.9	4.0	9.0	17.5	28.0	34.5	
	calc. $\bar{t}_g$	0.8	4.0	8.5	17.0	27.0	33.0	
38,500 (Standard)	t_{ex}	2.0	10.0	25.0	49.0	76.0	93.5	1.0
	t_g	2.3	11.0	24.0	47.0	75.0	93.0	1.0
35,500	t_{ex}	6.0	30.0	60.0	100.0	145.0	168.0	
	K_{ex}	0.33	0.33	0.42	0.49	0.52	0.56	0.44
	calc. t_{ex}	4.5	23.0	57.0	111.0	173.0	214.0	
	t_g	5.5	30.0	58.0	96.0	140.0	168.0	
	K_g	0.43	0.37	0.41	0.49	0.54	0.55	0.46
	calc. t_g	5.0	24.0	52.0	102.0	163.0	202.0	
	calc. $\bar{t}_g$	5.0	23.0	50.0	98.0	156.0	194.0	
33,500	t_{ex}	8.0	55.0	98.0	144.0	208.0	--	
	K_{ex}	0.25	0.18	0.26	0.34	0.37	--	0.25
	calc. t_{ex}	8.0	40.0	100.0	196.0	304.0	374.0	
	t_g	9.5	55.0	100.0	145.0	210.0	250.0	
	K_g	0.24	0.20	0.24	0.32	0.36	0.37	0.29
	calc. t_g	8.0	38.0	83.0	162.0	259.0	321.0	
	calc. $\bar{t}_g$	7.0	34.5	75.0	147.0	235.0	291.0	
31,500	t_{ex}	20.0	103.0	180.0	--	--	--	
	K_{ex}	0.10	0.10	0.14	--	--	--	0.12
	calc. t_{ex}	19.0	92.0	208.0	408.0	633.0	779.0	
	t_g	17.0	100.0	180.0	218.0	305.0	375.0	
	K_g	0.14	0.11	0.13	0.22	0.25	0.25	0.17
	calc. t_g	13.5	65.0	141.0	277.0	441.0	547.0	
	calc. $\bar{t}_g$	11.0	52.0	114.0	224.0	357.0	443.0	

Table VII (Cont'd.)

[ ] = Estimated or extrapolated value.

t_{ex} = Actual experimental times, from strain/time creep curves.

K_{ex} = "K" value based on $K_{ex} = \dfrac{t_{ex} \text{ for standard stress}}{t_{ex} \text{ for other stress}}$.

calc. t_{ex} = Calculated times for equation (2), using average K_{ex} for appropriate stress and t_{ex} for standard stress (38,500 psi).

t_g = Best average time, determined from stress/log time plots using t_{ex} values at specified strains.

K_g = "K" value based on $K_g = \dfrac{t_g \text{ for standard stress}}{t_g \text{ for other stress}}$.

calc. t_g = Calculated times from equation (2) using average K_g for appropriate stress and t_g for standard stress (38,500 psi).

calc. $\bar{t}_g$ = Calculated times from equation (2) using average K_g for appropriate stress from steady load steady temperature tests (see Table VIIc below) and t_g for standard stress (38,500 psi) under intermittent cycle 3 conditions.

Table VIIc. Average K_g Values for Steady Load Steady Temperature Tests. (Used in Calculation of Calc. $\bar{t}_g$ Above)

Average K_g for Total Strains	Stress psi	Average K_g for Creep Strains
2.9	42,000	2.8
1.0	38,500 (Standard)	1.0
0.56	35,500	0.48
0.40	33,500	0.32
0.30	31,500	0.21

determined from the test data, for total strains of 1% or greater. The values, calc. $\bar{t}_g$, predicted from the appropriate average values of K_g for the steady load isothermal data, and the times t_g to various total for a representative test at the standard stress under intermittent conditions, also agree well over the range 1% to the fracture, with the representative values of t_g at the other test stresses under intermittent conditions. Data predicted by both methods are plotted as strain versus time curves in Fig. 33(a). By using a standard stress of 38,500 psi, it may be seen that the predicted values calc. t_g or calc. $\bar{t}_g$, become less close to test data as the stress level of the predicted results becomes more removed from the chosen standard stress. In the case given as an example, some improvement can be made by using a standard stress closer to the stress for which data are to be predicted.

Further examination of Table VII and Fig. 33(b) will show that if the same analytical processes are applied to the times required to reach specified creep strains, as opposed to total strains, improved agreement is reached at the lower strain values, covering an equivalent total strain range of 0.5-1.0%. At the higher values of strain, however, the use of creep strain data causes a surprisingly greater deviation between predicted and actual values than is the case when total strain data are used. Further, the deviation increases more rapidly in the case of creep strain data, as the stress departs from the chosen standard stress. If agreement is sought over the largest possible range of creep, therefore, the total strain basis for analysis is to be preferred.

This same conclusion can be derived from a study of Tables VIII and IX in which both detailed and average K_g values are shown for the various cyclic conditions. Table VIII demonstrates that the condition involved

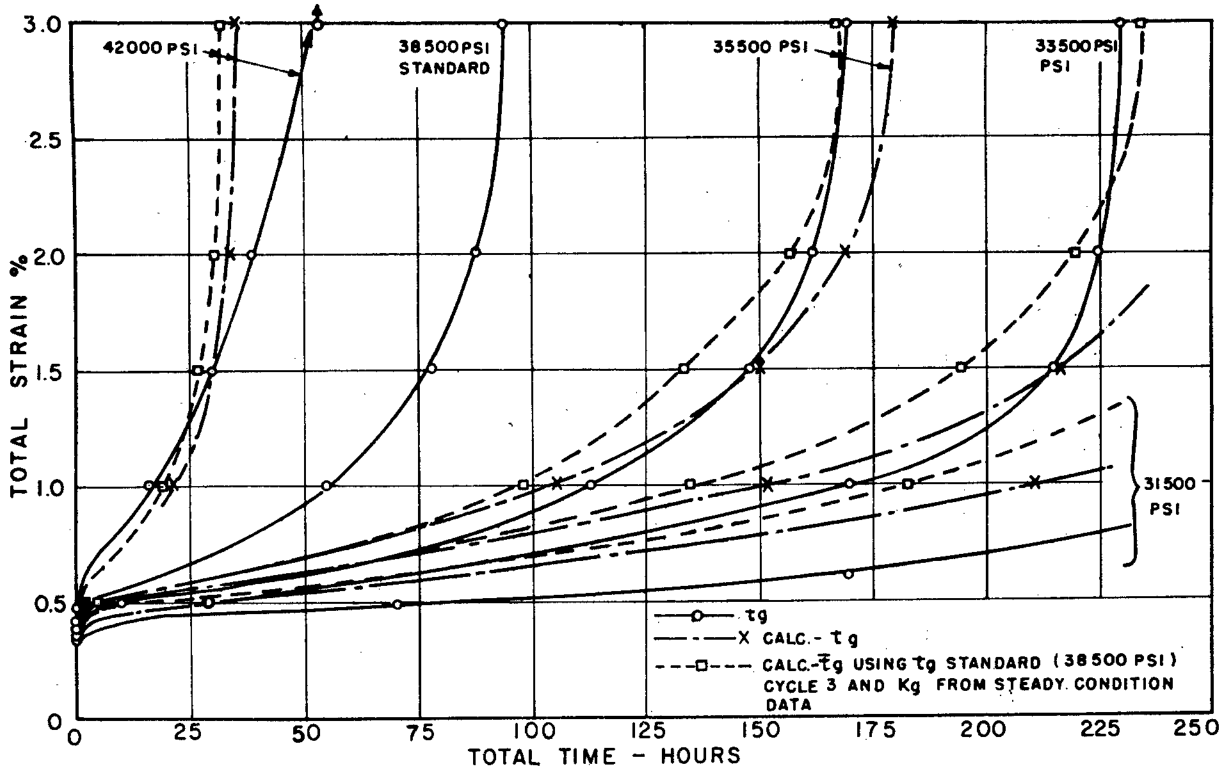


FIG. 33(a) PREDICTION OF CREEP DATA. TOTAL STRAIN/TOTAL TIME CURVES
75S-T6 300°F CYCLE 3

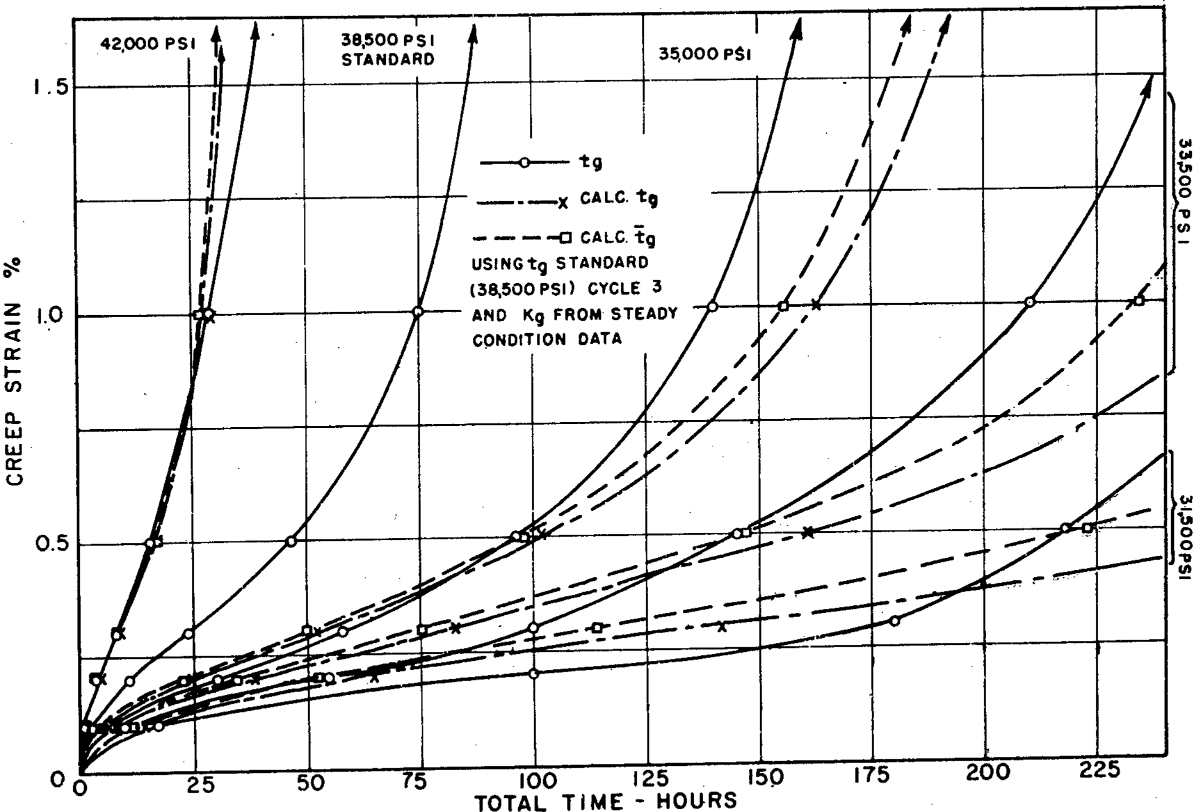


FIG. 33(b) PREDICTION OF CREEP DATA. CREEP STRAIN/TOTAL TIME CURVES 75S-T6
300°F CYCLE 3

TABLE VIII

Values of K_s at Various Stresses, Total Strains, and Intermittent Conditions. Creep of 75S-T6 at 300°F
Standard Stress = 38,500 psi (K = 1.0)

Table VIIIa. Total Strain Basis

Stress psi	Total Strain %	Steady Load and Temp.	Cycle 1	Cycle 2	Cycle 3	Cycle 5	Cycle 6	Cycle 7	Cycle 8
42,000	0.5	--	--	--	--	--	--	--	--
	1.0	3.0	2.6	2.1	3.4	3.4	3.5	2.5	3.0
	1.5	3.0	2.3	2.0	2.6	2.8	2.9	1.9	2.8
	2.0	2.8	2.2	1.9	2.3	2.6	2.8	1.8	2.64
	F	2.8	2.0	1.9	1.7	2.3	2.8	1.7	2.45
	Av.	2.9	2.1	1.95	2.6	2.7	2.9	1.9	2.7
35,500	0.5	--	0.89	0.27	0.10	0.19	0.09	--	--
	1.0	0.48	0.51	0.58	0.49	0.62	0.50	0.56	0.49
	1.5	0.56	0.54	0.60	0.53	0.65	0.56	0.58	0.55
	2.0	0.57	0.55	0.60	0.54	0.65	0.58	0.61	0.56
	F	0.60	0.57	0.61	0.55	0.64	0.63	0.65	0.57
	Av.	0.56	0.55	0.60	0.52	0.61	0.56	0.60	0.56
33,500	0.5	--	0.03	0.12	0.035	0.065	0.04	--	--
	1.0	0.30	0.35	0.40	0.32	0.44	0.33	0.39	0.32
	1.5	0.38	0.36	0.43	0.36	0.45	[0.40]	0.40	0.39
	2.0	0.42	0.38	0.44	0.39	0.46	--	[0.44]	0.41
	F	0.45	0.40	0.45	[0.41]	[0.48]	--	0.48	0.42
	Av.	0.40	0.37	0.43	0.36	0.46	0.41	0.42	0.39
31,500	0.5	--	0.01	0.06	0.014	0.024	0.021	--	--
	1.0	0.19	0.22	0.29	[0.22]	[0.34]	[0.24]	0.30	0.22
	1.5	0.27	0.25	0.31	[0.26]	[0.34]	--	0.28	0.28
	2.0	0.31	0.26	0.32	[0.28]	[0.34]	--	0.32	0.30
	F	0.34	0.28	0.34	--	--	--	--	0.32
	Av.	0.30	0.25	0.31	0.26	0.34	0.30	0.30	0.28

[ ] Uses Extrapolated Values

Table VIIIb. Creep Strain Basis

Stress psi	Creep Strain %	Steady Load and Temp.	Cycle 1	Cycle 2	Cycle 3	Cycle 5	Cycle 6	Cycle 7	Cycle 8
42,000	0.1	--	--	--	2.7	3.3	7.7	--	--
	0.2	0.26	3.43	3.44	3.0	3.5	7.7	3.5	2.52
	0.3	3.2	2.99	2.63	3.0	3.4	4.2	3.0	3.07
	0.3	2.9	2.44	2.38	3.0	3.5	3.5	2.5	3.04
	1.0	3.0	2.28	2.08	2.6	2.5	3.1	2.2	2.70
	2.0	2.8	2.13	1.89	2.1	2.4	2.8	2.2	2.45
	Av.	2.8	2.50	2.25	2.7	2.8	3.7	2.6	2.7
35,500	0.1	--	0.23	0.40	0.43	0.38	0.35	--	--
	0.2	0.42	0.44	0.49	0.37	0.37	0.40	0.64	0.49
	0.3	0.43	0.50	0.50	0.41	0.43	0.47	0.56	0.50
	0.5	0.47	0.53	0.54	0.49	0.58	0.53	0.58	0.52
	1.0	0.53	0.52	0.57	0.54	0.58	0.55	0.61	0.53
	2.0	0.56	0.55	0.60	0.55	0.60	0.60	0.61	0.57
	Av.	0.48	0.50	0.54	0.46	0.47	0.50	0.58	0.53
33,500	0.1	--	0.09	0.22	0.24	0.20	0.19	--	--
	0.2	0.25	0.26	0.33	0.20	0.18	0.26	0.35	0.31
	0.3	0.26	0.31	0.34	0.24	0.24	0.30	0.40	0.33
	0.5	0.29	0.32	0.39	0.32	0.41	0.37	0.42	0.37
	1.0	0.37	0.36	0.42	0.36	0.44	0.39	0.46	0.40
	2.0	0.41	0.38	0.44	[0.37]	[0.46]	--	[0.47]	0.41
	Av.	0.32	0.33	0.38	0.29	0.29	0.33	0.41	0.36
31,500	0.1	--	0.04	0.12	0.14	0.10	0.11	--	--
	0.2	0.14	0.16	0.26	0.11	0.09	0.18	0.25	0.20
	0.3	0.16	0.20	0.26	0.13	[0.15]	0.21	0.30	0.23
	0.5	0.19	0.22	0.30	0.22	[0.28]	0.26	0.31	0.26
	1.0	0.26	0.25	0.32	[0.25]	[0.33]	[0.29]	0.35	0.295
	2.0	0.31	0.27	0.34	[0.25]	--	--	--	0.31
	Av.	0.21	0.23	0.29	0.17	0.17	0.23	0.30	0.25

[ ] Uses Extrapolated Values

in the use of Eq. (2) for prediction purposes, namely that the value of the factor K is independent of strain, is not strictly fulfilled, the values of K_3 varying systematically with strain, and the spread of the values increasing as the stress departs from the chosen standard where $K = 1.0$. Fig. 34 shows the effect of both stress and strain on the K factor for the case of cycle 3 conditions. This might well be expected at 300°F where overaging will continue throughout the duration of the creep test, thus causing a continued change in the material undergoing creep as time increases during the test. It is likely that this would cause a change of K_3 with time, which is synonymous with a change of K_3 with strain.

Table IX shows the improvement effected by the averaging technique used in getting representative t_3 values. It can also be seen from this table that, in spite of the variation of K_3 with strain, as noted above, the average values do not vary excessively with the cyclic condition. As indicated in an earlier section, prediction of creep under intermittent conditions can therefore usefully be carried out with a minimum of testing under intermittent conditions, particularly if the stress range for which predicted data are required is not too large.

3. Analysis of 450°F Data

(a) Net Time Approach

Only one cycle (cycle 3) was used in the tests conducted in the present program, since studies of the effect of the other intermittent conditions had already been made.(4,5,6) As was found during the presently reported series of tests at 300°F, the test results obtained in the current investigation under cycle 3 conditions were not entirely compatible

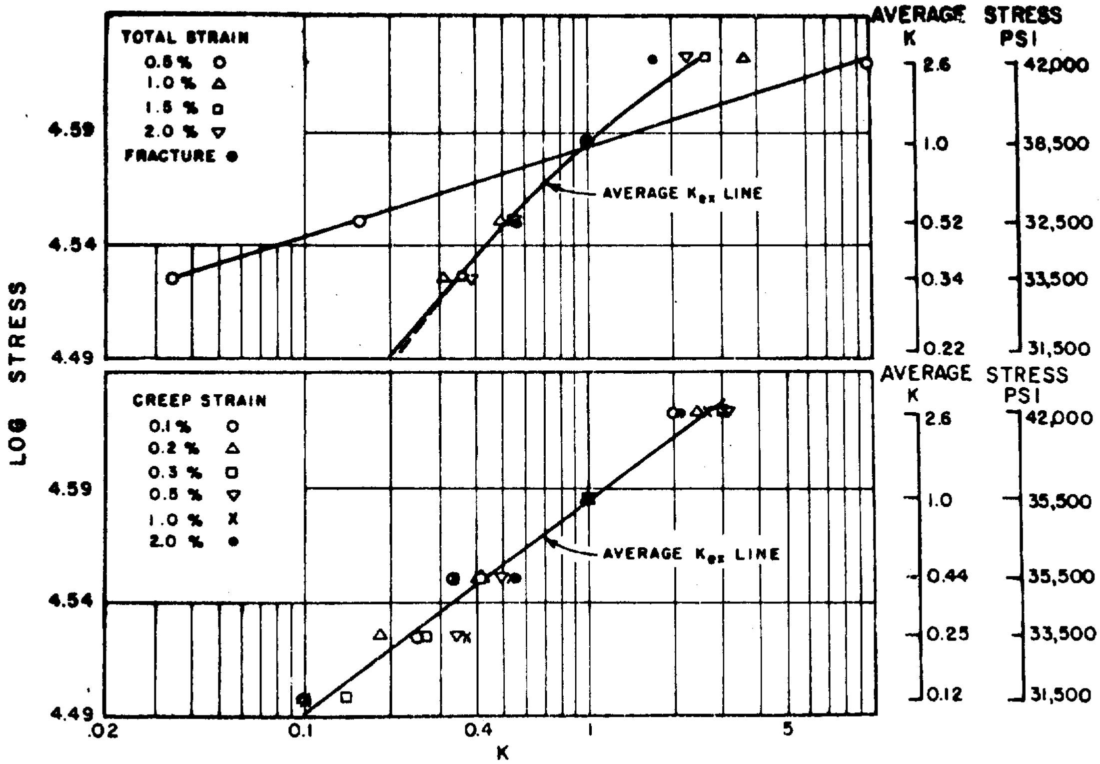


FIG. 34 (a) VARIATION OF K_{ex} WITH STRESS AND STRAIN
75 S-T6 300°F CYCLE 3

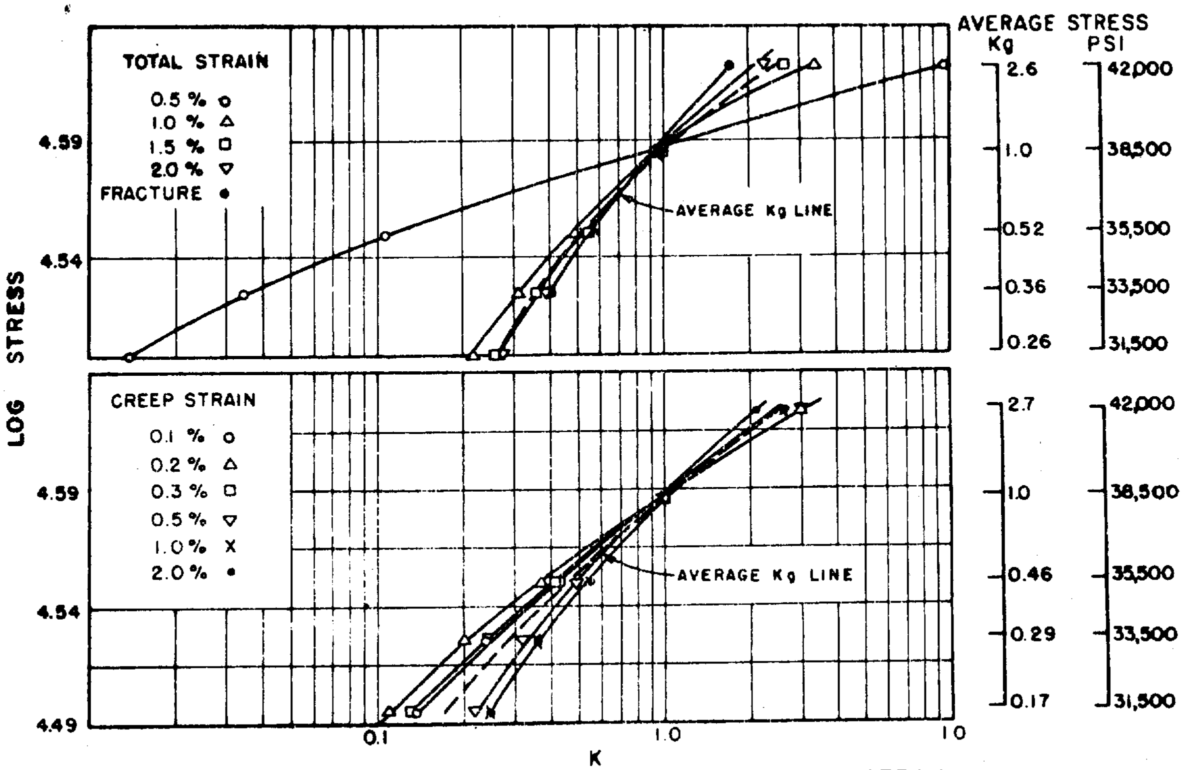


FIG. 34 (b) VARIATION OF Kg WITH STRESS AND STRAIN
75 S-T6 300°F CYCLE 3

TABLE IX

Average Values of K_{ex} and K_g for Various

Stresses and Intermittent Conditions

Creep of 75S-T6 at 300°F

	Stress	SLST	Cycle 1	Cycle 2	Cycle 3	Cycle 5	Cycle 6	Cycle 7	Cycle 8	% Deviation from SLST +	% Deviation from SLST −
Total Strain Values											
K_{ex}	42,000	3.0	2.2	2.0	2.6	2.8	3.1	1.6	2.6	3	47
K_g	"	2.9	2.1	1.95	2.6	2.7	2.9	1.9	2.7	--	34
K_{ex}	38,500	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	--	--
K_g	"	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	--	--
K_{ex}	35,500	0.56	0.53	0.58	0.52	0.60	0.60	0.47	0.55	7	16
K_g	"	0.56	0.55	0.60	0.52	0.61	0.56	0.60	0.56	9	7
K_{ex}	33,500	0.40	0.38	0.42	0.34	0.46	0.41	0.34	0.38	15	15
K_g	"	0.40	0.37	0.43	0.36	0.46	0.41	0.42	0.39	15	10
K_{ex}	31,500	0.31	0.25	0.31	0.22	0.36	0.32	0.26	0.27	16	29
K_g	"	0.30	0.25	0.31	0.26	0.34	0.30	0.30	0.28	13	13
Creep Strain Values											
K_{ex}	42,000	2.9	2.55	2.20	2.6	3.4	4.0	2.2	2.9	38	24
K_g	"	2.8	2.50	2.25	2.7	2.8	3.7	2.6	2.7	32	14
K_{ex}	38,500	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	--	--
K_g	"	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	--	--
K_{ex}	35,500	0.50	0.48	0.56	0.44	0.62	0.43	0.51	0.55	24	14
K_g	"	0.48	0.50	0.54	0.46	0.47	0.50	0.58	0.53	21	4
K_{ex}	33,500	0.33	0.32	0.40	0.25	0.49	0.26	0.36	0.37	48	24
K_g	"	0.32	0.33	0.38	0.29	0.29	0.33	0.41	0.36	29	9
K_{ex}	31,500	0.21	0.24	0.30	0.12	0.40	0.20	0.28	0.26	95	43
K_g	"	0.21	0.23	0.29	0.17	0.17	0.23	0.30	0.25	43	19

SLST = Steady Load, Steady Temperature

with those previously described in the above references. The present series showed the material to be considerably weaker at the lower stresses under intermittent temperature cycle 3 conditions when compared with the early steady load isothermal data although agreement was good at the higher stresses. This conclusion is unlikely to be correct, and is contradictory to the previous results and to the results obtained in the extensive tests of the present series at 300°F. Further, at 300°F, shorter times were required to reach specified strains or fracture in the present steady load isothermal tests than in those conducted earlier. It was considered that the differences might perhaps be explained by differences in testing techniques, but check tests mentioned earlier showed that the change in the initial heating cycle of the test piece before the application of the first load was not responsible. It was also considered possible that the long storage of the material ($3\frac{1}{2}$ years) might have resulted in slight changes in its properties. Check tensile tests agreed closely with those carried out when the material was first delivered, but it was still possible that although no change in tensile properties could be detected, the creep properties may have been affected particularly at the slower creep rates since it is well known that the creep properties of many materials are very sensitive to minute changes in structure. A well known example is the effect of different deoxidising agents on the creep rate of killed open hearth steels.[11] When, however, the repeated Series II tests at 300°F under cycle 7 conditions, and the 600°F steady load isothermal tests were done on the same sheet of specimen stock and both these sets of results indicated a creep strength greater than that found by other tests in the presently reported work, and more compatible with earlier reported data[4], it seemed most probable that the differences discussed arise

arise from variation between the sheets of specimen stock material.

(b) Analytical Correlation and Prediction

Application of the methods of correlation and prediction already described to the present cycle 3 test data at 450°F gave good results. The K_y factor appears to be much more independent of strain over the range from 0.5% total strain to fracture, than was the case at 300°F, and excellent agreement between experimental and predicted curves was obtained. Table X and Figs. 35 and 36 illustrate these points. The greater independence of the K values at 450°F than at 300°F with respect to strain agrees with the suggested explanation offered for the 300°F case. At 450°F any overaging at test temperature is probably completed early in the test, and subsequent changes in the material due to this cause are minor. No changes in the K values as the test continues are therefore to be expected due to this cause.

It will be seen from Fig. 35 and Table X that at 450°F, as at 300°F, the correlation procedure adopted is much more successful when total strains are used than when the analysis is conducted on the basis of creep strain.

4. Analysis of 600°F Data

(a) Net Time Approach

In agreement with the comparisons discussed at 450°F between the data of the present test series, and previously reported data,(4,6) certain differences between the two sets of results appear to exist. As was the case at 450°F, agreement between the two groups of data is good for the higher stress shorter time tests, but in the present series the material now appears weaker in the longer time lower stress tests than previously reported results indicated. For this reason a new series of

TABLE X

K_g Values for Various Stresses, Strains, and Intermittent Conditions. Creep of 75S-T6. 450°F. Cycle 3.

Table Xa. Total Strain Basis

Stress psi	K_g for Total Strains of:							Average (Graphical) K_g
	0.5%	1.0%	1.5%	2.0%	3.0%	5.0%	Fracture	
12,000	5.1	4.6	4.7	4.6	4.6	4.6	4.6	4.6
10,000	1.38	1.33	1.33	1.34	1.34	1.32	1.33	1.34
9,500	Standard Stress. All = 1.0							
9,000	0.75	0.75	0.74	0.75	0.74	0.75	0.73	0.76
8,600	0.59	0.60	0.59	0.60	0.59	0.59	0.58	0.60
8,200	0.46	0.48	0.48	0.48	0.48	0.49	0.49	0.47

Table Xb. Creep Strain Basis

Stress psi	K_g for Creep Strains of:							Average (Graphical) K_g
	0.1%	0.2%	0.3%	0.5%	1.0%	2.0%	5.0%	
12,000	--	5.3	5.1	4.6	4.4	4.4	4.4	4.7
10,000	--	1.19	1.22	1.18	1.20	1.26	1.25	1.30
9,500	Standard Stress. All = 1.0							
9,000	--	0.84	0.85	0.81	0.78	0.75	0.76	0.78
8,600	--	0.76	0.72	0.67	0.61	0.58	0.55	0.64
8,200	--	0.70	0.60	0.52	0.43	0.38	--	0.52

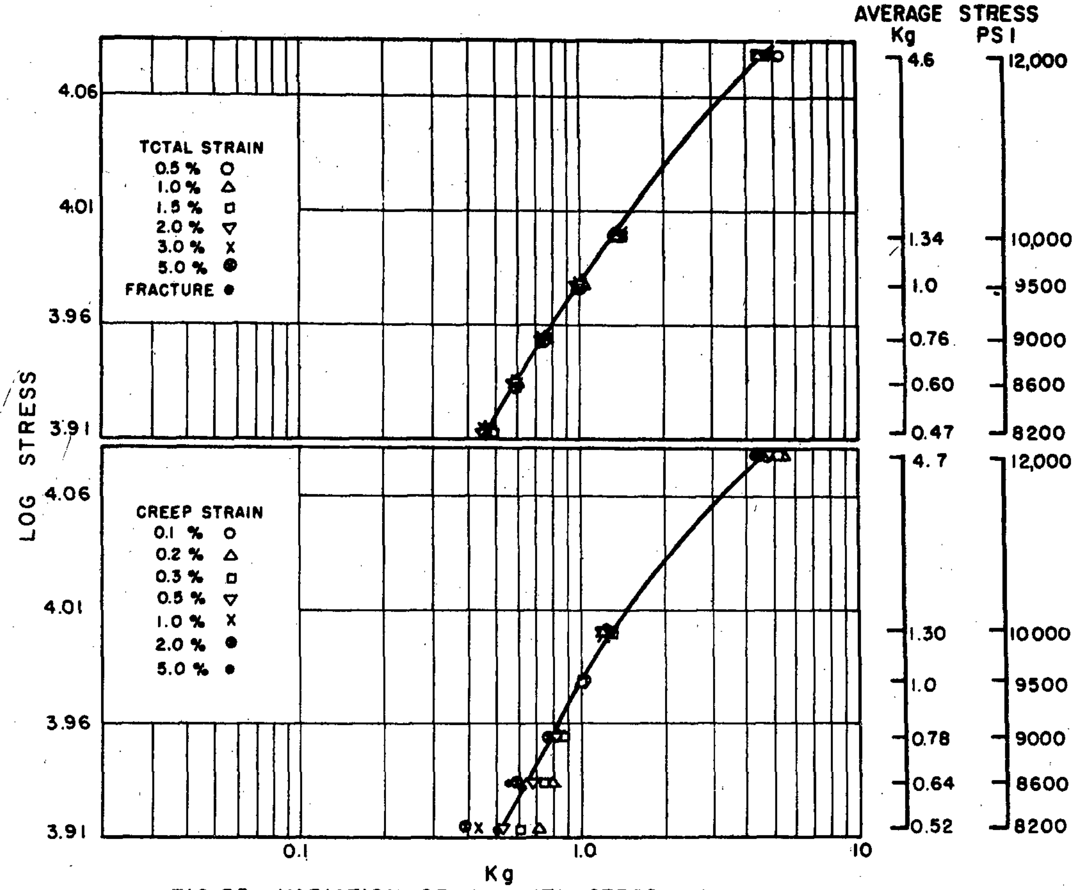


FIG. 35 VARIATION OF K_g WITH STRESS AND STRAIN
75 S-T6 450° F CYCLE 3

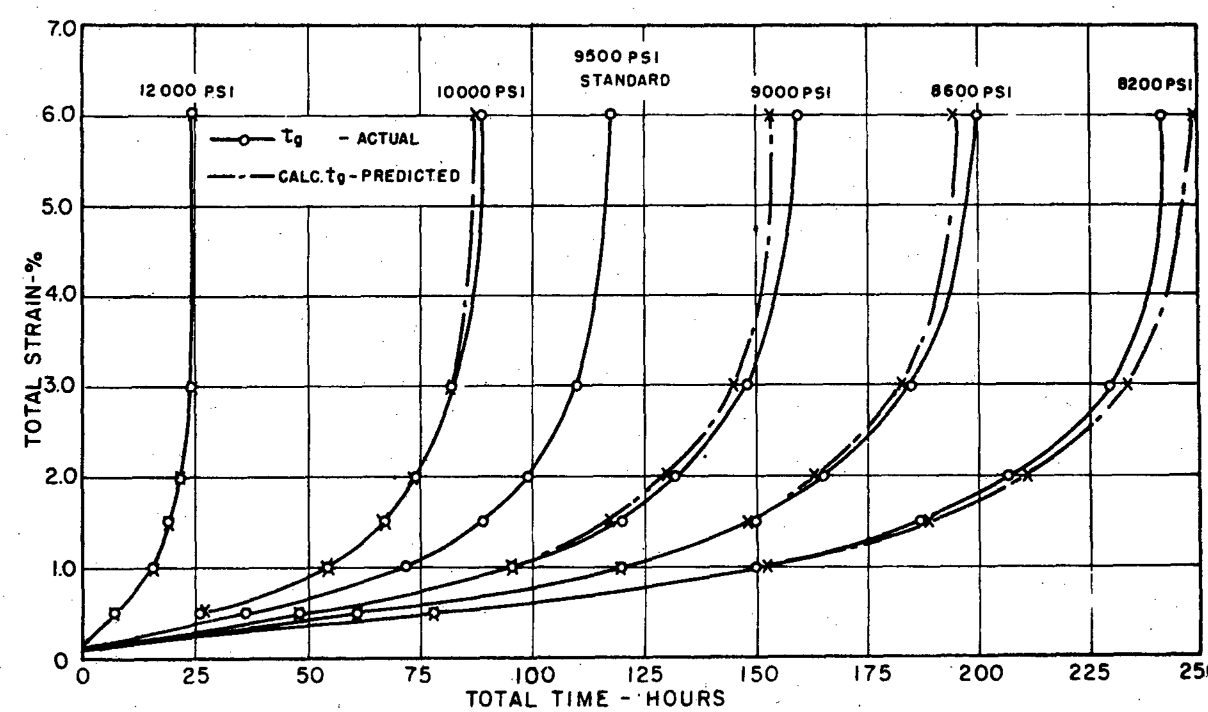


FIG. 36 PREDICTION OF CREEP DATA TOTAL STRAIN/ TOTAL TIME CURVES
75 S-T6 450 °F CYCLE 3

steady load isothermal tests were conducted to provide a basis for comparing the tests of the presently reported series by the net time method. As previously described the results obtained were compatible with earlier reported data[4], but indicated somewhat greater strength, particularly at the lower stresses than presently reported intermittent data. These differences are considered to arise from slight differences between the various sheets of specimen stock.

A comparison is made in Table XI, where it may be seen that in general the various cyclic conditions appear to have no systematic effect on the creep behavior of 75S-T6 alloy at 600°F. A possible exception to this generalization exists for the steady load, intermittent heating conditions of cycle 3, particularly at the lower stresses. The increased creep apparently resulting from this cause may most probably be ascribed to small amounts of deformation occurring during the heating portion of each cycle, where the temperature begins to approach 600°F, and the test load is operative. The same conditions exist to a more restricted degree in the combined out of phase cycle 8. Here, although the specimen is under load during the heating portion of each cycle, the rate of heating is greater, and the effect suggested would be considerably less. The slightly lower values of the net time to specified strains for the longer times support this suggestion.

The approximate equivalence of all the cyclic test conditions employed at 600°F, as opposed to the marked weakening effects observed at 300°F for some cycles, supports the explanation previously offered. The recovery and overaging processes, which are considered primarily responsible for the reduction in creep strength at 300°F in those cases when the specimen is subjected to elevated temperature in the absence of load, will undoubtedly

TABLE XI

Comparison of Average Net Times (Net t_a) to Reach Specified Strains for Various Cyclic Conditions

Creep of 75S-T6 at 600° F

Stress psi	Total Strain %	Steady Load and Temp.	Cycle 3	Cycle 5	Cycle 6	Cycle 7	Cycle 8
5,000	0.2	1/2	1/4	1/4	--	1/2	--
	0.5	2	1	1 1/2	1	1 1/2	1 1/2
	1.0	4 1/4	2 1/4	3	2 1/2	4	3
	1.5	6	3 3/4	4 1/2	4	6	4 1/2
	2.0	7 1/2	4 3/4	5 3/4	5	8 1/4	6
	3.0	10	6 1/2	7 1/2	6 3/4	11 1/4	7 1/2
	5.0	13	9	10	8 1/2	15	10
	F	18	12 1/2	11 1/2	11 1/4	18 1/4	13 1/4
4,500	0.2	3/4	1/2	1/2	1/4	1/2	--
	0.5	3	2 1/2	2 1/2	2 1/2	1	3
	1.0	7 1/2	5 1/2	6 1/2	6 3/4	7 1/2	6 1/2
	1.5	12	8	10	10	12	10
	2.0	15 1/2	11	13 1/4	13	16 1/4	13
	3.0	20 1/2	15 1/2	17	17 1/2	23	17 1/2
	5.0	29	21	23 1/2	26	31	23 1/2
	F	41	29	30	38	40 1/2	32
4,000	0.2	1 1/4	1	1/2	1/2	1 1/4	--
	0.5	6	5 1/2	5	6 1/2	5 1/2	6
	1.0	17	12 1/2	14	18	16 1/2	14 1/2
	1.5	27 1/2	19 1/2	23 1/2	26	26 1/4	21 1/2
	2.0	37	25	33	34	35	29
	3.0	50	34 1/2	42 1/2	47 1/2	51	41 1/2
	5.0	72	48	60	--	70	61
	F	102	68	88	--	94	88
3,500	0.2	3	2	1 1/2	3 1/4	2 1/4	--
	0.5	16	13 1/2	12	16 1/4	13 1/2	12 1/2
	1.0	43	26 1/2	32	50	40	33
	1.5	66	42	60	[70]	65	52 1/2
	2.0	90	57	90	--	86	73
	3.0	128	80	--	--	150	113
	5.0	190	110	--	--	--	--
	F	250	--	--	--	--	--
3,200	0.2	7	2 3/4	2 1/2	7	4	--
	0.5	31	21	20 1/2	27	27	21 1/2
	1.0	78	40	55	[87]	79	55
	1.5	18	66	113	[115]	131	98
	2.0	160	93	--	--	184	140
	3.0	230	130	--	--	--	--
	5.0	[330]	[180]	--	--	--	--
	F	--	--	--	--	--	--

[ ] = Estimated or Extrapolated Data

take place very much more rapidly at 600°F. Overaging will be complete at a very early stage of the test, while the effects of deformation at 300°F which are recovered slowly at this temperature in the absence of load, are unlikely to occur at 600°F, where tensile results indicate that recovery is very rapid.

(b) <u>Analytical Correlation and Prediction</u>

The procedures used to analyze the test data obtained at 300°F have been applied to the 600°F data, with the exception that for reasons given previously, the test results have been expressed only in terms of total strain, the creep strain data being omitted. Tables XII and XIII summarize the results of correlation by the K factor, while Figs. 37 and 38 provide examples of the prediction of creep data by the use of this correlation for cycle 3 conditions (steady load, intermittent temperature, 1 hr./1 hr.). On the whole prediction of the 600°F data showed somewhat better agreement with the average experimental values than was the case for 300°F, but the same tendencies were found for increased deviation of the predicted creep curve from the experimental curve as the stress became more remote from the standard stress on which the correlation was based. Agreement of the average K values for the same stress applied under different cyclic conditions was close, confirming the postulate that the stress function, f, of Eq. (1) is, to a good approximation, independent of the cyclic condition. Consequently the maximum use may be made of the prediction methods developed, and the calculation of data at any stress (within a moderate stress range) under intermittent conditions requires only one test at some standard stress under the intermittent condition, and sufficient steady load isothermal creep data to evaluate the K for the unknown stress in relation to the standard. Alternatively at 600°F a fair approximation for the

TABLE XII

Values of K_s at Various Stresses, Total Strain and Intermittent Conditions. Creep of 75S-T6 at 600°F. Standard Stress = 4,500 psi (K_s = 1.0).

Stress psi	Total Strain %	New SLST	Cycle 3	Cycle 5	Cycle 6	Cycle 7	Cycle 8
5,000	0.2	1.40	1.96	1.60	--	1.76	--
	0.5	1.50	2.35	1.76	2.44	1.89	2.0
	1.0	1.76	2.44	1.94	2.70	2.02	2.10
	1.5	2.00	2.33	2.22	2.58	2.06	2.15
	2.0	2.07	2.34	2.30	2.60	2.00	2.17
	3.0	2.05	2.38	2.27	2.59	2.03	2.33
	5.0	2.23	2.33	2.35	3.06	2.05	2.35
	F	2.28	2.32	2.61	3.16	2.16	2.42
	Av.	2.05	2.35	2.30	2.60	2.05	2.20
4,000	0.2	0.56	0.49	0.51	0.24	0.53	--
	0.5	0.50	0.43	0.49	0.40	0.49	0.48
	1.0	0.44	0.44	0.46	0.37	0.48	0.45
	1.5	0.44	0.45	0.43	0.38	0.47	0.47
	2.0	0.42	0.44	0.40	0.39	0.47	0.45
	3.0	0.41	0.45	0.40	0.37	0.45	0.42
	5.0	0.40	0.44	0.39	--	0.44	0.39
	F	0.40	0.43	0.34	--	0.43	0.37
	Av.	0.45	0.45	0.45	0.38	0.45	0.45
3,500	0.2	0.23	0.25	0.22	0.55	0.27	--
	0.5	0.19	0.17	0.21	0.16	0.20	0.23
	1.0	0.17	0.21	0.20	0.14	0.20	0.20
	2.0	0.17	0.19	0.15	--	0.19	0.18
	3.0	0.16	0.19	--	--	0.15	0.16
	5.0	0.15	0.19	--	--	--	--
	F	0.16	--	--	--	--	--
	Av.	0.18	0.20	0.20	0.16	0.18	0.19
3,200	0.2	0.100	0.18	0.12	0.026	0.16	--
	0.5	0.097	0.11	0.12	0.097	0.10	0.13
	1.0	0.096	0.14	0.12	0.077	0.10	0.12
	1.5	0.100	0.13	0.089	0.087	0.094	0.10
	2.0	0.097	0.12	--	--	0.090	0.093
	3.0	0.089	0.12	--	--	--	--
	5.0	0.088	0.12	--	--	--	--
	F	--	--	--	--	--	--
	Av.	0.097	0.12	0.12	0.070	0.10	0.11

TABLE XIII

Average Values of K_{ex} and K_g for Various Stresses and Intermittent Conditions

Creep of 75S-T6 at 600°F (Total Strain Values)

Value	Stress psi	SLST	New SLST	(4) Cycle 1	(4) Cycle 2	Cycle 3	Cycle 5	Cycle 6	Cycle 7	Cycle 8
K_{ex}	5,700	8.2		10.0	7.5	—	—	—	—	—
K_g	"	—		—	—	—	—	—	—	—
K_{ex}	5,000	—	1.8	—	—	2.4	3.1	2.8	2.05	2.4
K_g	"	—	2.05	—	—	2.35	2.3	2.6	2.05	2.2
	4,500 (Standard)	All K Values = 1.0								
K_{ex}	4,200	—	—	—	—	—	—	0.58	—	—
K_g	"	—	—	—	—	—	—	0.56	—	—
K_{ex}	4,000	0.36	0.40	0.41	0.38	0.44	0.45	0.40	0.46	0.45
K_g	"	—	0.45	—	—	0.45	0.45	0.38	0.45	0.45
K_{ex}	3,500	0.14	0.17	0.18	0.18	0.20	0.22	0.18	0.19	0.22
K_g	"	—	0.18	—	—	0.20	0.20	0.16	0.18	0.19
K_{ex}	3,200	0.086	0.09	0.11	0.14	0.13	0.14	0.11	0.10	0.15
K_g	"	—	0.097	—	—	0.12	0.12	0.07	0.10	0.11

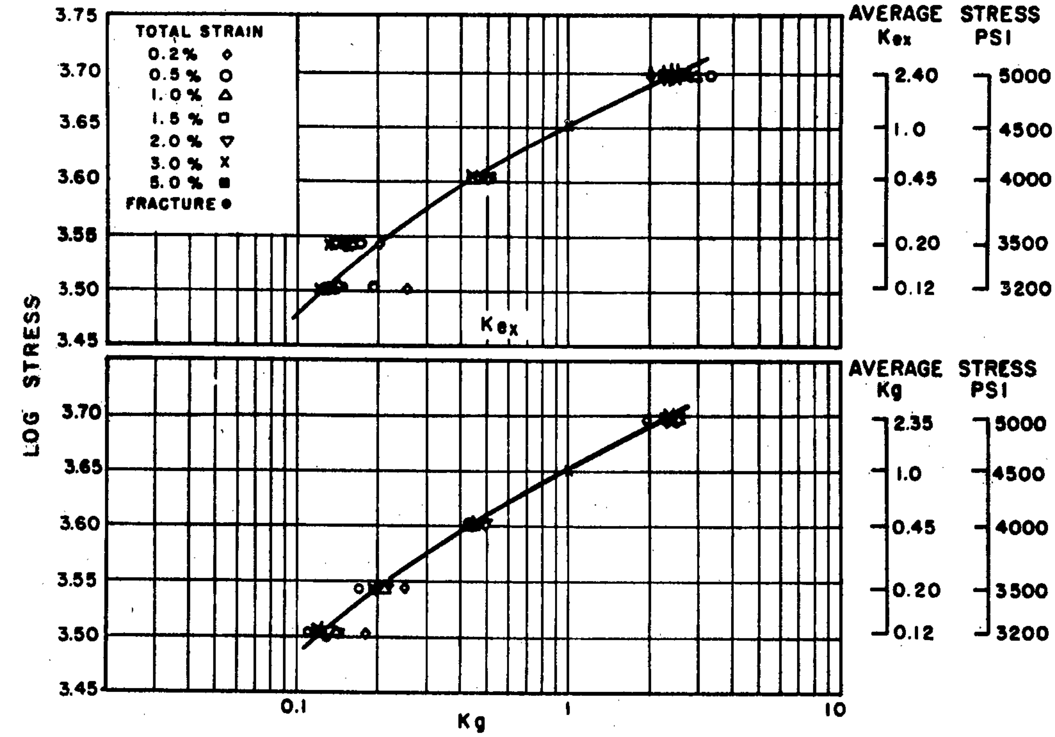


FIG. 37 VARIATION OF K VALUES WITH STRESS AND STRAIN
75S-T6 600°F CYCLE 3

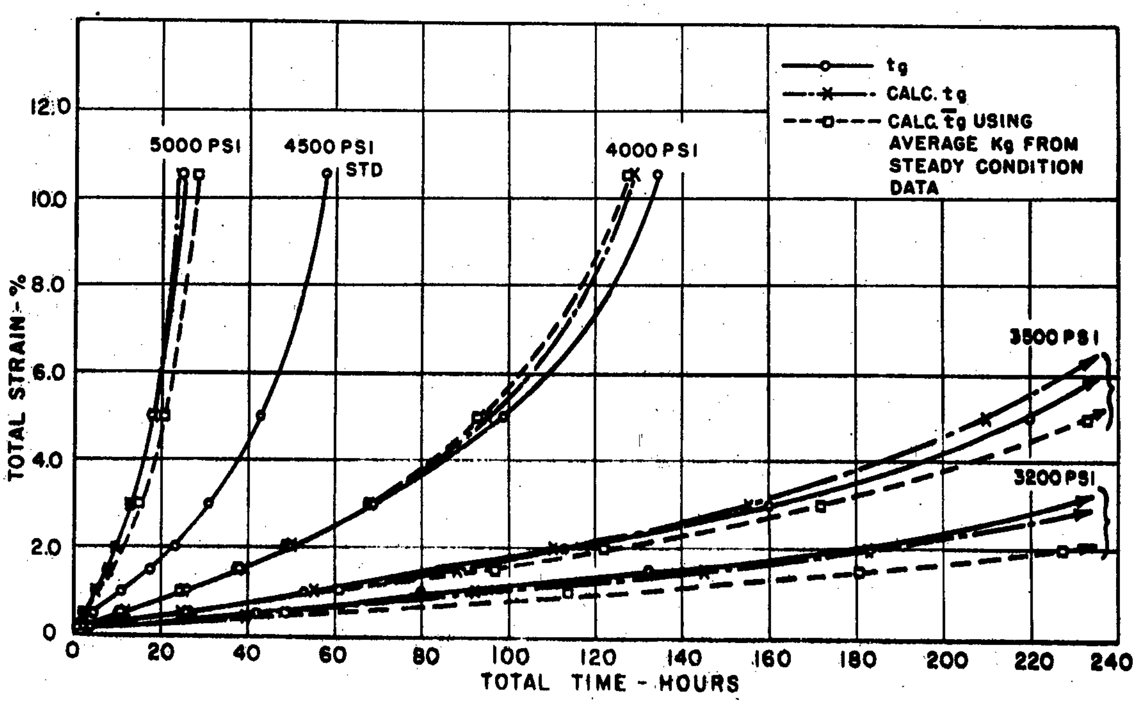


FIG. 38 PREDICTION OF CREEP DATA TOTAL STRAIN/TOTAL TIME CURVES
75S-T6 600°F CYCLE 3

intermittent condition may be achieved as described in the previous section by using the total strain values obtained from a steady load isothermal test reached in the same net time under load at the test temperature.

EVALUATION OF ANALYTICAL METHODS

1. Introduction

The successful use of methods of analysis and prediction of creep data developed and discussed in this and previous reports has so far been demonstrated only for a relatively limited range of intermittent conditions, and in detail for only one material - aluminum alloy 75S-T6. The detailed analysis of these results has not only shown that for most of the cases examined good agreement between calculated and actual creep curves can be obtained at moderate strains but it has also shown that the K factor involved in the method is insensitive to the type of cycle involved in tests under intermittent conditions, at least within the range of the eight cases studied. This detailed analysis has also disclosed a weakness in the method, inasmuch as the factor K is slightly dependent on strain, its variation with strain (or time) increasing as the test stress becomes further removed from the standard stress of the analysis. It was therefore considered necessary to conduct an extensive survey of available creep data from both steady load isothermal tests, and from intermittent condition tests in order to assess the validity, and the range of application of the proposed methods of analysis. The former type of data could be used to evaluate the extent to which the K factor might vary with strain, and to established whether the basic equation

$$\varepsilon = F\left\{t f(\sigma)\right\}$$

previously proposed could be applied to the prediction of creep data in general, or whether restrictions on its range of validity were imposed by such variables as type and composition of material, stress range, strain range, and duration of the test. These limitations would be additional to the obvious condition that the above equation cannot be valid when large plastic strains are produced on application of the test stress. An analysis has also been made of the results of creep tests under several types of intermittent conditions carried out at Cornell Aeronautical Laboratories Inc.[7,8] on a number of materials, in order to test the apparent independence of the K factor with respect to the type of intermittent test condition observed in the present series of tests.

2. Criteria for Evaluation

Up to the present, it has been considered desirable for the predicted times to reach various strains at some specified stress to be within $\pm 20\%$ of the average experimental value. For strains of about 1% this criterion would represent agreement of the same order as the normal scatter found in creep testing many commercial alloys. However, it may be that this standard is unneccessarily rigid, particularly at low strains. The design information often required is the value of the stress which will cause specified strains or fracture in given times. In many cases an error of $\pm 20\%$ in the times involved is associated with a considerably lower percentage error in the corresponding value of the stress. The data for the steady load isothermal creep of 75S-T6 alloy at 300°F have been used to illustrate this point. The values of calc. t_g for specified total strains at the five test stresses have been replotted as stress/log time curves, and the stress required to produce strains of 1.0%, 1.5%, 2.0% and fracture in times of 20, 50, 100 and 150 hrs. determined from the graphs. Fig. 39 shows the actual and calculated stress/log time curves. In Table XIV(a) the comparison of calculated and experimental data is made on a time basis, while in Table XIV(b) the comparison is made on the stress basis described above. It may be seen that the difference using the latter criterion is for the most part negligible from the design viewpoint, even though appreciable differences exist when the corresponding comparison is made on a time basis. At low stresses and longer times, when the stress/log time diagrams often become flatter, considerable differences in times to reach a specified strain may still correspond to an unimportant difference in permissible design stresses. Judgment as to the effectiveness or otherwise of the proposed prediction procedures must therefore be related not to any absolute standard of agreement, but to the permissible design tolerances required by considerations such as operational stress, minimum endurance, permissible maximum deformation, and material characteristics.

One further point may be made before consideration of the methods and results of the detailed survey of data which has been carried out. It is certain that no empirical method of analysis of creep data can be universally applied. Consideration of the effect of such complications as metallurgical changes during the progress of creep, and the effect of creep itself in changing the initial structure of a material exposed to the combined influence of stress and temperature make it fundamentally impossible to arrive at general laws of creep[12] which can be extensively applied to commercial alloys until our knowledge of creep behavior and processes is much more advanced than at present. Even partial success in the application of methods of analysis and prediction which is likely to assist in the reduction of the quantity of testing, particularly

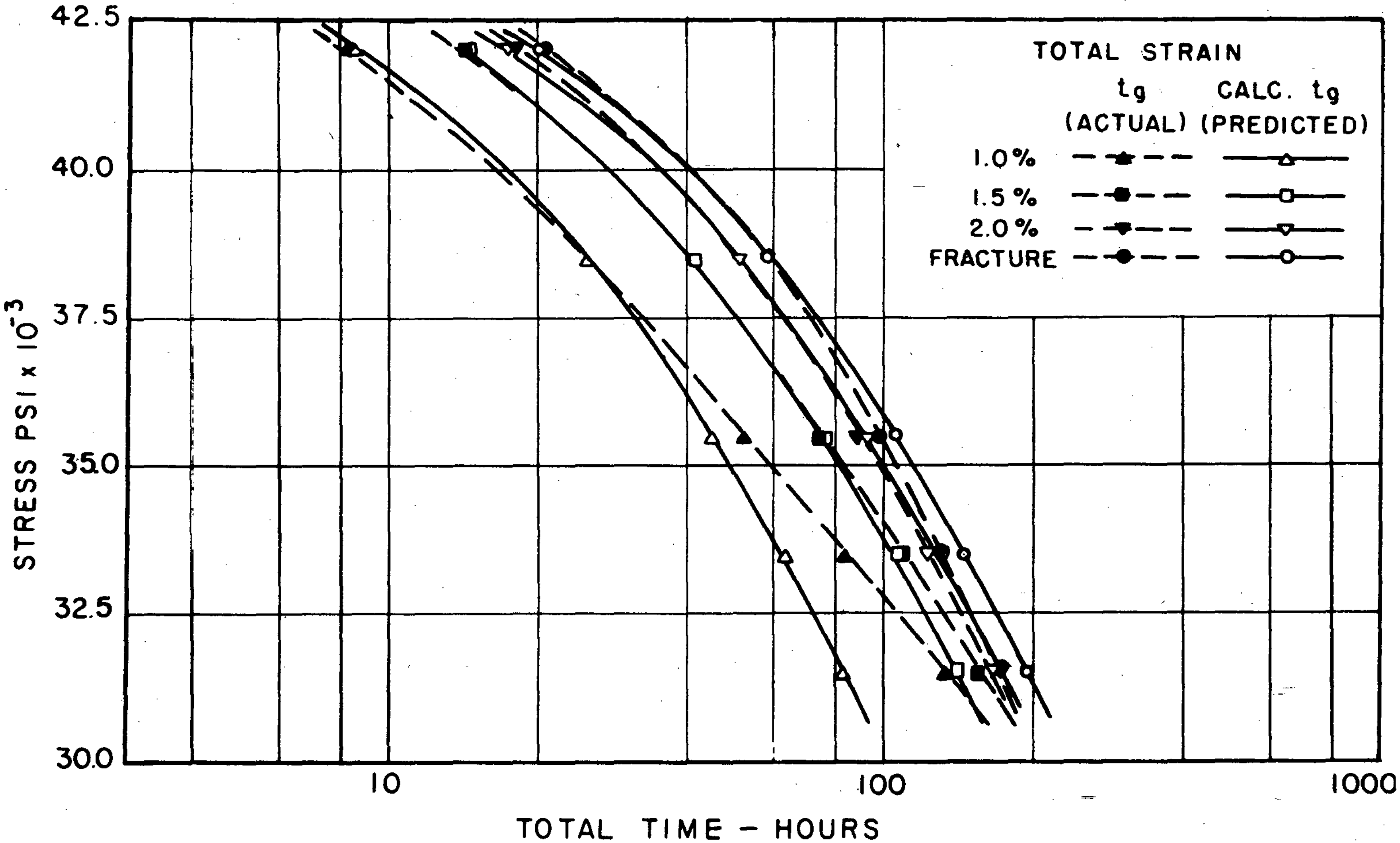


FIG. 39 ACTUAL AND CALCULATED STRESS/LOG TIME CURVES 75S-T6
300° F STEADY LOAD AND TEMPERATURE

TABLE XIV

Comparison of Experimental and Calculated Creep Data for Steady Load, Isothermal Creep of 75S-T6 at 300°F

Table XIVa. Comparison on Time Basis

Stress psi	Total Times (Hrs.) to Reach Specified Total Strains							
	Experimental (ϵ_3)				Calculated (calc. ϵ_a)			
	1.0%	1.5%	2.0%	Fracture	1.0%	1.5%	2.0%	Fracture
42,000	8.3	14	18	20½	8.6	14½	17½	20
38,500 (Standard)	25.0	42	51	58	—	—	—	—
35,500	52.0	72	90	97	45.0	75	91	104
33,500	84.0	110	122	130	63.0	107	128	145
31,500	135.0	155	165	170	83.0	140	170	193

Table XIVb. Comparison on Stress Basis

Time Hrs.	Stresses (psi)x10^{-3} to Produce Specified Total Strains							
	Experimental				Calculated			
	1.0%	1.5%	2.0%	Fracture	1.0%	1.5%	2.0%	Fracture
20	39.3	41.2	41.7	42.0	39.5	41.3	41.7	42.0
50	35.7	37.6	38.6	39.2	34.9	37.7	38.7	39.2
100	32.9	34.0	34.8	35.3	30.2	33.8	35.1	35.7
150	31.0	31.6	32.2	32.5	27.0	31.1	32.3	33.2

testing under intermittent heating and stressing, may therefore be considered to represent some progress in the study of creep under these conditions.

3. Methods of Evaluation

In the application of the basic equation

$$\varepsilon = F\left\{t f(\sigma)\right\} \tag{1}$$

previously proposed, it has been assumed that the stress function, f, is independent of strain, and consequently

$$\frac{{}_{\varepsilon_1}t_s}{{}_{\varepsilon_1}t_\sigma} = K = \frac{{}_{\varepsilon_2}t_s}{{}_{\varepsilon_2}t_\sigma} \tag{5}$$

where ${}_{\varepsilon_1}t_s$ = total time at some standard stress to reach a total strain ε_1

${}_{\varepsilon_1}t_\sigma$ = total time at some other stress, σ, to reach a total strain ε_1

${}_{\varepsilon_2}t_s$ = total time at the standard stress to reach a total strain ε_2

${}_{\varepsilon_2}t_\sigma$ = total time at the other stress, σ, to reach a total strain ε_2

In fact it has been found that K is not truly independent of strain, and further that the variation in K increases as the stress, σ, departs from the standard stress. The variation in K with strain has therefore been used to study the validity of Eq. (1), while the average value of K with respect to strain at various stresses has been used to estimate whether the prediction of intermittent data can be accomplished from steady load isothermal test results and only one intermittent test. Such a prediction relies on the independence of f and therefore K, with respect to intermittent conditions. Studies of the variations in the value of K have therefore been made for the data from Cornell Aeronautical Laboratories Inc.[7,8] in addition to the analysis made in preceding sections of the data accumulated in these laboratories.

Such a detailed study of the vast body of available steady load isothermal creep data is manifestly not possible within the time available, and more rapid methods of evaluation have therefore been applied. Where data are presented as creep curves of strain (or log strain) plotted against the logarithm of the time, the analysis proposed is applicable when the curves at a series of stresses are displaced relative to each other along the log time axis by a distance approximately independent of strain for any pair of curves. From Eq. (5), at any pair of values for the standard stress and the stress σ, the stress/log time design curves for the specified total strains ε_1 and ε_2 will be equally spaced with respect to the log time axis, as may be seen in the calculated curves of Fig. 39. The deviation of the experimental curves from parallelity can therefore be used as an indication of the success or failure of Eq. (1). Further, if the stress function, f, is independent of the cyclic condition, the stress/log time curves for any intermittent creep testing condition should be parallel with those derived from steady load isothermal data at each and every value of the specified strain. The position of a set of curves under any given test condition will, of course, vary, such variation being controlled by the strain function, F, of equation (1).

4. Application of Steady Load, Isothermal Creep Data

From the detailed analysis of the data presented in this and previous related reports, it seemed probable that accurate prediction of steady load isothermal creep data by the methods proposed would be subject to limitations of both stress and strain. The use of the graphical comparison methods described in the previous section has made it possible to examine over one hundred and fifty sets of creep curves for a variety of materials. References to the currently published data examined are given in the bibliography at the end of this report.[13-22] In no case was any correlation found to cover the entire strain and stress range of a series of tests, but in approximately one third of the cases examined the proposed analytical method appeared to give useful results over reasonable ranges of stress and strain. Creep curves at relatively low test temperatures for several commercial aluminum alloys (24S-T, 75S-T, R301-T[13], 2S, 4S[14], 63S-T[15]) in various conditions did not appear to constitute homologous series of the type indicated by Eq. (1), but correlation was considerably improved at temperatures of about 350°-400°F. At these temperatures κ factor values (and hence predicted times to reach specified strains) appeared to be usually within ±20% of a mean value over a range of stresses which would produce fracture in times from 50-800 hrs., and over a total strain range of from 1.0% to fracture (5-10%). The results of Sherby and Dorn on annealed aluminum 2S-0[16] and on 99.6%[14,16] aluminum could not be consistently correlated for any of four temperatures (90°F-400°F) or for any annealed condition within tolerances of approximately 50% in times to reach various strains. Creep data on high purity aluminum and a series of dilute solid solution alloys of aluminum with copper, magnesium, zinc, and germanium at 300°F[17] gave reasonably constant κ values over stress ranges capable of producing rupture in from 10 hrs. to 500 hrs. and for a strain range of approximately 10% to fracture (50-60%). The creep of dilute aluminum silver alloys,[17] however, did not fit in with the analysis, the κ values varying with strain by a factor of up to 2 even over very restricted ranges of stress. Creep data on some austenitic and ferritic gas turbine disc alloys[18,19,20] did not show good agreement with Eq. (1), except at certain temperatures, but some success was experienced with creep data on Inconel X, and much of the long time creep data on the nickel-chromium base British high temperature alloys Nimonic 80, Nimonic 80A, and Nimonic 90[21] could be effectively correlated within reasonable limits of accuracy, even for strains as low as 0.1% and for test times in some cases over 10,000 hours. The extensive data of Cross and Simmons[22] on a wide variety of heat resisting gas turbine alloys provided further evidence of useful agreement with Eq. (1), usually over restricted ranges of stress and strain, in approximately one third of the families of creep curves or stress/log time design curves examined.

Although the general survey of steady load isothermal creep data so far completed must be considered as indicating qualitatively rather than quantitatively the degree of agreement of experimental results with the functional Eq. (1), it is apparent that its application to the correlation and prediction of steady load isothermal data is by no means universal. No effective generalizations as to when the method is likely to be successful can be made, and its use must therefore be a matter of judgment for each individual case under consideration. When it is used flexibly, and with due regard to the limitations of stress or strain range encountered in any particular application, it would seem that considerable benefit may be derived from its use as a means of interpolating and extrapolating existing data complementary to such well known methods as the use of stress/log time design curves.

5. Application to Published Intermittent Condition Creep Data

The survey of the foregoing section has shown that in a proportion of steady load isothermal creep data, the variation of K with strain is sufficiently minor as to render feasible the prediction and correlation of such data by the use of Eqs. (4) or (5). The experimental studies of this and previous reports indicate that where this is the case, the value of K is also approximately independent of the steady or intermittent nature of the test temperature or the applied stress. In order to check this, the intermittent and steady condition creep data[7,8] determined at the Cornell Aeronautical Laboratories, Inc. for a variety of materials were subjected to detailed analysis. No other intermittent condition creep data suitable for such study have been uncovered.

(a) Magnesium Alloy FS-1H[7,8]

For the creep of FS-1H magnesium alloy at 300°F, remarkable agreement of the experimental data with the predicted data was found when the K factors for the appropriate test condition was applied. An example of this agreement is shown in Fig. 40, for a steady temperature intermittent load (1 hr. on, 1 hr. off) cycle. In this case, creep curves have also been predicted by the application of the average K factors at the various stresses, derived from the steady load isothermal data, to the single standard stress curve under the intermittent condition, and again, excellent agreement has been obtained. A similar procedure applied to the prediction of data with a steady temperature 1½ hr. off/½ hr. on intermittent stress cycle, or with a cycle employing steady load intermittent temperature (1 hr. at temperature/ 2 hr. total cycle) also gave good correlation, as may be seen from Table XV where intermittent and steady condition average K values are given.

At 450°F the analysis of the data is less satisfactory, since in many cases strains of 2% were reached in times of less than one cycle,

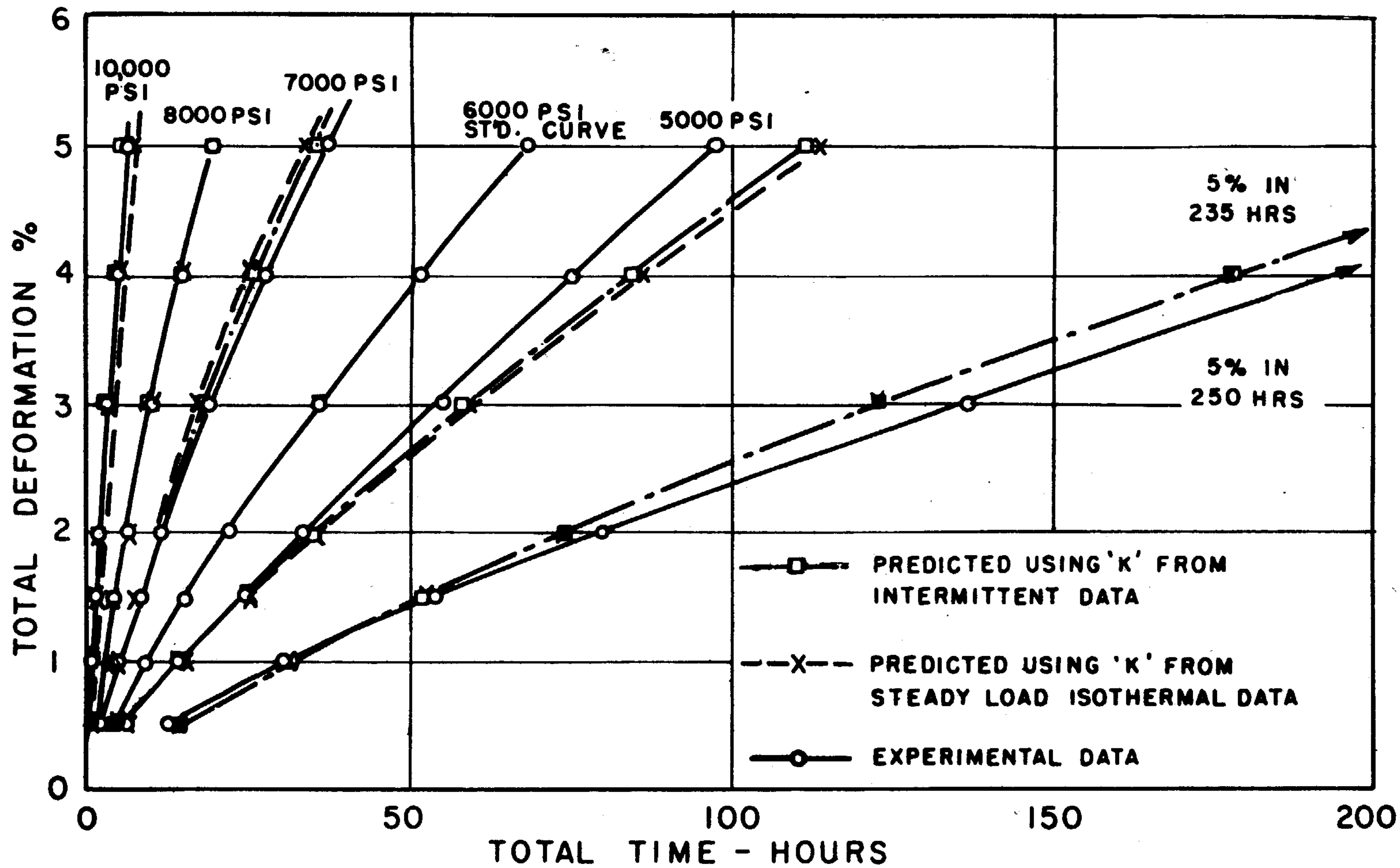


FIG. 40 CREEP OF FS - 1 HR MAGNESIUM, CONSTANT TEMPERATURE 300° F
INTERMITTENT LOAD 1 HR ON / 1 HR OFF
EXPERIMENTAL AND PREDICTED CURVES

TABLE XV

Average K Factor Values for Various Stresses and Intermittent Conditions. Creep of FS-IH Magnesium Alloy

Table XV(a). 300°F. 1% Total Strain - Fracture

Stress psi	SLST	ILST 1 hr. on/ 1 hr. off	ILST ½ hr. on/ 1½ hr. off	ILIT 1 hr. on/ 1 hr. off
3,000	0.106	—	0.105	—
4,000	[0.25]	0.27	—	—
4,100	0.28	—	—	—
5,000	0.53	0.56	0.50	0.46
6,000 (Standard)	1.00	1.00	1.00	1.00
7,000	[1.75]	1.70	1.84	1.92
7,100	1.88	—	—	—
8,000	3.06	3.18	3.48	3.09
10,000	8.8	10.7	11.3	8.3
12,000	25.5	33.0	32.0	19.2

Table XV(b). 450°F. 1% - 5% Total Strain

Stress psi	SLST	ILST 1 hr. on/ 1 hr. off	ILST ½ hr. on/ 1½ hr. off	SLIT 1 hr. on/ 1 hr. off
650	0.155	—	—	—
1,000	0.37	0.38	0.42	0.42
1,650 (Standard)	1.00	1.00	1.00	1.00
2,000	1.52	1.43	1.48	—
2,350	[2.15]	—	—	2.0
3,150	4.00	3.6	3.8	4.1
4,100	[7.9]	—	—	—
5,000	10.0	—	10.8	—

NOTE: Based on data from Cornell Aeronautical Laboratories, Inc.[7,8]

[ ] = Interpolated Value.
SLST = Steady Load, Steady Temperature
ILST = Intermittent Load, Steady Temperature
SLIT = Steady Load, Intermittent Temperature

and such times cannot be considered as representative of true intermittent condition behavior. For strains of 1%-5% consistent values of the K factor were obtained, which did not appear to be appreciably affected by the type of intermittent cycle employed in the test. The average K factors evaluated from the data with due regard to the above limitations are given in Table XV. Fracture data at 450°F have not been included in this analysis, since it was found that the method could not satisfactorily be applied in this instance, and only data for strains up to 5% have been made use of where the times involved have been adequate to include the effect of intermittent conditions. As for the 300°F data, the average K values quoted are taken from a smooth curve drawn through the experimental points on a log stress/log K plot.

(b) 24S-T3 Aluminum Alloy[7,8]

Test results suitable for analysis for intermittent load, intermittent temperature, and combined intermittent load and temperature conditions embodying six different cycles were available at 450°F and 600°F in addition to the steady load isothermal creep data. Variation of the value of the K factors with strain for any particular stress and intermittent condition was not excessive, falling within ±10% of the average value in all except a few cases, and in many instances being considerably more consistent over a strain range of 0.5% to fracture (approximately 3%). In many cases where the deviations were large, use of adjusted values of the times to reach given strains, derived from stress/log time diagrams, would effectively remove or reduce the discrepancy. However, when the average K values for the same stress applied under the various intermittent conditions are compared, as in Table XVI(a), a rather large variation is apparent.

TABLE XVI

K Factor Values for Various Stresses and Intermittent Conditions Creep of 24S-T3 Aluminum Alloy

Table XVI(a). 450°F. 0.5% Total Strain - Fracture (approx. 3%)

Stress psi	SLST	ILST 1 Hr./ 1 Hr.	ILST ½ Hr./ ½ Hr.	ILST 8 Hrs./ 8 Hrs.	SLIT 1 Hr./ 1 Hr.	SLIT ½ Hr./ 1½ Hr.	SLIT Sch. 1	ILIT Sch. 2	% Deviation from SLST +	% Deviation from SLST −
15,000	0.22	0.34	0.37	—	0.20	—	—	—	68	9
17,000	0.39	0.50	0.55	0.33	0.39	—	0.53	0.35	41	15
20,000 (Std.)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	—	—
22,000	1.85	2.15	2.10	1.75	1.85	1.4	1.7	2.0	16	24
25,000	4.9	7.0	5.8	3.3	4.0	5.0	3.9	4.6	43	20

Table XVI(b). 600°F. 0.5% Total Strain - Fracture (approx. 10%)

Stress psi	SLST	ILST 1 Hr./ 1 Hr.	ILST ½ Hr./ ½ Hr.	ILST 8 Hrs./ 8 Hrs.	SLIT 1 Hr./ 1 Hr.	SLIT ½ Hr./ 1½ Hrs.	SLIT Sch. 1	ILIT Sch. 2	% Deviation from SLST +	% Deviation from SLST −
4,000	0.13	0.10	0.056	0.15	—	—	—	—	15	57
5,000	0.40	0.37	0.40	0.42	0.47	0.50	0.44	0.51	27	7
6,000 (Std.)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	—	—
7,000	2.25	2.2	2.2	2.0	2.0	1.85	2.15	1.80	0	20
8,000	4.6	4.3	3.8	3.75	3.5	3.0	4.0	3.1	0	35
10,000	17.0	14.0	10.0	—	9.2	6.0	12.0	7.5	0	65

SLST = Steady Load and Temperature
ILST = Intermittent Load, Steady Temperature
SLIT = Steady Load, Intermittent Temperature
ILIT = Combined Intermittent Load and Temperature

NOTE: Based on data from Cornell Aeronautical Laboratories, Inc.[7,8]

Although the K factors at the lower stresses show considerably greater variation with strain the data at 600°F follow a somewhat similar pattern to that described for the 450°F results, as may be seen from Table XVI(b). While in both cases a more detailed treatment involving the use of average times derived from stress/log time curves, and the discounting of apparently anomalous results leads to some improvement in the consistency of results, it would still seem that the use of average K values obtained from steady load isothermal data, in conjunction with a single test at the standard stress under the intermittent condition, would lead to predicted data which would in many instances fail to agree with the actual data within reasonable limits for the material and test temperatures under consideration.

(c) Low Carbon N-155 Alloy[8]

An attempt to correlate the creep data at 1350°F and 1500°F for this high temperature gas turbine alloy was not entirely satisfactory. For some series of tests, particularly those under intermittent temperature conditions, the variation of K with strain and stress was erratic. The results are given in detail in Table XVII, the average K values at each stress being obtained from a smooth curve drawn through the points at the various strains plotted on log stress/log K graphs. In some instances the average K values were also corrected to take into account the effect of an apparently non-typical test at the standard stress. Although the average K values obtained by these methods for three of the four cycles show fair agreement, prediction of strain/time data did not give good agreement with the experimental creep curves except for a few instances.

(d) Inconel X[8]

By using the averaging methods described in the previous section,

TABLE XVII

K Factor Values for Various Stresses, Strains, and Intermittent Conditions. Creep of Low Carbon N-155 Alloy.

Table XVII(a). 1350°F

Stress psi	Total Strain %	SLST	ILST 1 hr. on/ 1 hr. off	ILST 8 hrs. on/ 8 hrs. off	SLIT 1 hr. on/ 1 hr. off
20,000	0.5	--	0.18	--	--
	1.0	0.14	0.08	--	--
	2.0	0.092	--	--	--
	5.0	0.056	--	--	--
	Fracture	0.065	--	--	--
	Average	0.11	0.12	--	--*
24,000	0.5	0.38	0.44	0.20	0.71
	1.0	0.29	0.40	0.37	0.14
	2.0	0.34	0.33	0.44	0.19
	5.0	0.32	0.28	0.39	--
	Fracture	0.28	0.33	0.29	0.40
	Average	0.37	0.38	0.37	--*
26,000	0.5	0.67	0.86	0.77	0.26
	1.0	0.52	0.76	0.74	0.28
	2.0	0.54	0.71	0.75	0.35
	5.0	0.50	0.66	0.84	--
	Fracture	0.54	0.69	0.58	0.69
	Average	0.62	0.64	0.65	--*
28,000	Standard Stress - All K's = 1.0				
30,000	0.5	1.43	1.50	1.09	2.12
	1.0	1.27	1.37	4.67	1.04
	2.0	1.22	1.33	1.28	0.87
	5.0	1.19	1.47	1.46	--
	Fracture	1.10	1.84	1.17	1.53
	Average	1.39	1.50	1.43	--
35,000	0.5	--	--	--	--
	1.0	--	7.7	--	--
	2.0	5.9	4.0	8.9	5.15
	5.0	2.43	3.5	3.4	--
	Fracture	2.02	3.8	2.8	5.6
	Average	3.1	4.0	2.8	--*

SLST = Steady Load and Temperature
ILST = Intermittent Load, Steady Temperature
SLIT = Steady Load, Intermittent Temperature

NOTES: 1. Data from Cornell Aeronautical Laboratories, Inc.[8]

2. Average K values obtained from smooth average curve through points on log stress/log K plot. Correction applied where required for apparently non-typical creep curve at standard stress.

* Scatter of points on log stress/log K plot such that no significant average values could be obtained.

Table XVII(b). 1500°F

Stress psi	Total Strain %	SLST	ILST 1 hr. on/ 1 hr. off	ILST 8 hrs. on/ 8 hrs. off	SLIT 1 hr. on/ 1 hr. off
12,000	0.5	0.036	0.079	--	--
	1.0	0.033	--	--	--
	2.0	0.038	--	--	--
	5.0	0.050	--	--	--
	Fracture	0.067	--	--	--
	Average	0.038	--	--	--
13,500	0.5	0.089	0.10	--	0.11
	1.0	0.096	0.087	--	0.15
	2.0	0.11	0.098	--	--
	5.0	0.13	0.12	--	--
	Fracture	0.17	0.14	--	0.28
	Average	0.115	0.13	--	--*
15,000	0.5	0.21	0.30	--	0.42
	1.0	0.28	0.37	0.26	0.27
	2.0	0.28	0.36	0.25	--
	5.0	0.31	0.38	0.30	--
	Fracture	0.36	0.32	0.31	0.56
	Average	0.31	0.30	0.27	--*
17,000	Standard Stress. All $K_s' = 1.0$				
19,000	0.5	--	3.91	--	--
	1.0	3.44	3.88	--	1.43
	2.0	3.34	3.06	--	2.22
	5.0	2.70	2.81	2.41	--
	Fracture	2.31	1.9	2.02	1.94
	Average	3.0	3.0	2.4	--*
21,000	0.5	--	--	--	--
	1.0	--	7.6	--	4.7
	2.0	7.4	6.6	6.2	6.7
	5.0	6.0	5.5	3.7	3.1
	Fracture	4.7	3.9	3.5	3.1
	Average	6.1	7.0	3.8	--*

SLST = Steady Load and Temperature
ILST = Intermittent Load, Steady Temperature
SLIT = Steady Load, Intermittent Temperature

NOTES: 1. Data From Cornell Aeronautical Laboratories, Inc.[8]
2. Average K values obtained from smooth average curve through points on log stress/log K plot.
* Scatter of points on log stress/log K plot such that no significant average values could be obtained.

good agreement was obtained between the average K values for the two intermittent cycles and the steady load and temperature creep data for this material at 1500°F (Table XVIII). At 1350°F, somewhat greater differences between the steady and cyclic load isothermal tests were found although at this temperature the variation of K values with strain was less than at 1500°F, where deviations from the mean value were in some cases of the order of 50%.

(e) Titanium Alloy RC 130-A[8,23]

Due to the shape of the creep curves for this material at 600°F, characterized by a very sharp turn over of the strain/time curve, data for RC 130-A titanium alloy at this temperature could not be effectively analyzed. At 700°F, however, fairly good correlation both within and between steady and intermittent load isothermal tests was obtained over the strain range 2.0% to fracture (approx. 30%). The average K values obtained as previously described are given in Table XIX. Data on the steady load intermittent temperature condition were insufficient for effective analysis. At 800°F only a limited range of stresses could be successfully correlated, and therefore no correlation factors for this temperature have been reported.

(f) Type 321 Stainless Steel[8]

The creep test data for this material have been analyzed for both 1200°F and 1350°F test series. At 1200°F, data for the steady load intermittent temperature cycle are not considered sufficient to obtain reliable average values. For the steady and intermittent load isothermal tests fairly good correlation was obtained within and between the two series for the strain range 1.0% to fracture (approx. 10%). The average K values

TABLE XVIII

Average K Factor Values for Various Stresses and Intermittent Conditions

Creep of Inconel X

1350°F				1500°F			
Stress psi	SLST	ILST 1/1	SLIT 1/1	Stress psi	SLST	ILST 1/1	SLIT 1/1
25,000	0.10	--	Not sufficient data to obtain significant average K values.	11,000	0.17	--	--
30,000	0.23	--		13,000	[0.3]	--	0.37
35,000	0.50	0.39		15,000	0.52	0.55	0.56
40,000	1.0	1.0		18,000	1.0	1.0	1.0
45,000	2.7	2.3		20,000	1.5	1.44	1.43
50,000	7.8	5.1		25,000	3.2	3.3	3.4

[ ] = Interpolated Data

NOTE: Data from Cornell Aeronautical Laboratories, Inc.(8)

SLST = Steady Load and Temperature
ILST = Intermittent Load, Steady Temperature
SLIT = Steady Load, Intermittent Temperature

TABLE XIX

Average K Factor Values for Various Stresses and Intermittent Conditions. Creep of Titanium Alloy RC 130-A, 700°F

Stress psi	SLST	ILST 1 hr. on/1 hr. off
55,000	0.23	0.24
65,000	0.42	0.44
75,000	0.72	0.75
80,000	Standard, K's = 1.0	
85,000	1.44	1.48
90,000	2.24	--
100,000	7.8	5.5

NOTE: Data from Cornell Aeronautical Laboratories, Inc.

SLST = Steady Load and Temperature
ILST = Intermittent Load, Steady Temperature

for the two cases are given in Table XX(a).

At 1350°F fairly good correlation was again obtained for the steady and intermittent load isothermal creep data, but agreement was less satisfactory for the steady load intermittent temperature cycle. Table XX(b) gives the average K values at the various stresses at 1350°F, while a comparison of experimental and calculated, creep curves has been made in Figs. 41 and 42. Fig. 41 demonstrates the results of applying the analysis to the steady load and temperature data, while in Fig. 42 the predicted curves for the intermittent temperature steady load case are shown in which the average K factors for the steady load isothermal case have been applied to the standard stress creep curve of the intermittent condition.

6. <u>Results of Evaluation of Analytical Method</u>

From a study of a representative body of steady load isothermal creep data on a variety of metals, it is apparent that the proposed functional equation

$$\varepsilon = F\left\{t f(\sigma)\right\}$$

while not generally applicable to all creep data, can be usefully employed in about one third of the cases examined. For most aluminum alloys, it seems that correlation is more satisfactory at temperatures above about 400°F, and may be better for simple solid solutions than for the relatively complex commercial alloys. For other materials no grouping of alloys, even on an approximate basis, has so far been uncovered which would indicate in advance whether the creep data for a given alloy were likely to be amenable to analysis or not. In all those cases where the method does appear applicable, limitations are usually to be found with respect

TABLE XX

Average K Factor Values for Various Stresses and Intermittent Conditions. Type 321 Stainless Steel

Table XX(a). 120°F. 1.0% Total Strain to Fracture (approx. 10%)

Stress psi	SLST	ILST 1 hr. on/1 hr. off
20,000	0.34	--
22,000	0.51	0.52
25,000	Standard Stress, K's = 1.0	
27,000	1.48	1.65
30,000	2.95	3.3
33,000	7.4	6.5

Table XX(b). 1350°F. 0.5% Total Strain to Fracture (approx. 10%)

Stress psi	SLST	ILST 1 hr. on/ 1 hr. off	SLIT 1 hr. on/ 1 hr. off
9,000	0.205	—	0.29
10,000	0.285	0.22	0.37
12,000	0.56	0.49	0.61
14,000	Standard Stress, K's = 1.0		
17,000	2.45	2.9	2.55
20,000	7.5	7.6	6.4

NOTE: Data from Cornell Aeronautical Laboratories, Inc.(8)

SLST = Steady Load and Temperature
ILST = Intermittent Load, Steady Temperature
SLIT = Steady Load, Intermittent Temperature

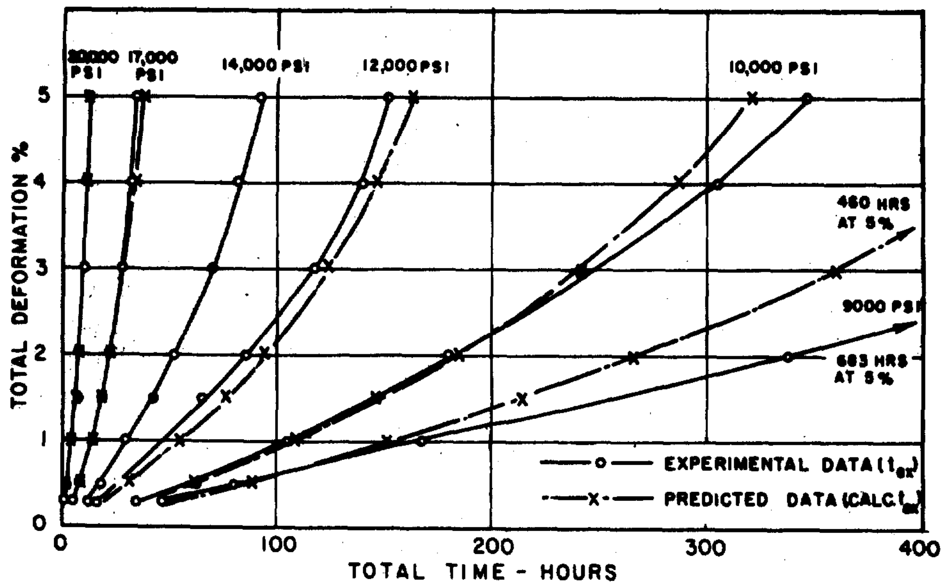


FIG. 41 EXPERIMENTAL AND PREDICTED CREEP CURVES TYPE 321 STAINLESS STEEL STEADY LOAD AND TEMPERATURE 1350°F (DATA BY CORNELL AERONAUTICAL LAB'S. INC[8])

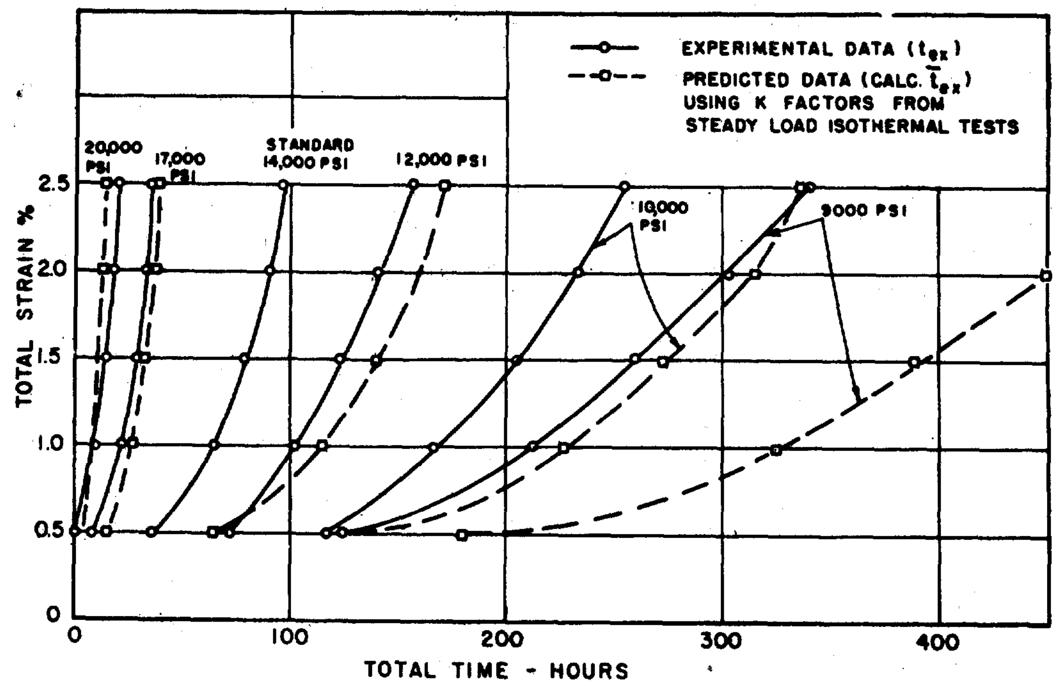


FIG. 42 EXPERIMENTAL AND PREDICTED CREEP CURVES TYPE 321 STAINLESS STEEL INTERMITTENT HEATING 1350°F (DATA BY CORNELL AERONAUTICAL LAB'S. INC[8])

to the range of both stress and strain over which satisfactory correlation and prediction of data can be achieved, and while useful results can be obtained by using the proposed method of analysis as a complement to well established interpolation and extrapolation procedures, such as the use of stress (or log stress) versus log time design curves, flexibility and judgment are required in its application. Present experience has indicated that the limitations of the proposed method arise from the fact that the stress function, f , is not independent of strain, and Eq. (1) is in fact an excessive simplification implying as it does an equation of state which, as has been demonstrated, cannot be generally applied to creep.

If, however, in the cases and over the ranges where Eq. (1) is a fair approximation, the stress function, f , is the same for steady load isothermal creep, and creep under most types of intermittent load and/or temperature cycle, much testing time and expense can be saved by the prediction of the intermittent creep data by the use of one or two chosen intermittent tests and the appropriate K factor determined from existing, or readily obtainable steady load isothermal creep tests. The analyses of results of creep tests carried out both in these laboratories, and at Cornell Aeronautical Laboratories, Inc., indicate that this is generally the case, and that in many instances fairly good agreement between prediction and experiment is obtainable over a useful range. Although accurate predictions are not generally possible the lack of experimental data on the creep of materials under intermittent conditions of loading and heating is such that even relatively crude quantitative estimates of such data are likely to be useful until more experimental data, and a more rigorous method of analysis based on a sound fundamental approach are available.

CONCLUSIONS

1. The results of creep testing clad aluminum alloy 75S-T6 at 300°F under isothermal-intermittent load, under steady load-intermittent temperature, and under in-phase and out-of-phase cycles of combined intermittent load and temperature conditions, show that the various cycles may be broadly divided into two groups, according to whether they affect the net time under load at elevated temperature to reach fracture or specified total strains. Those cases where processes of recovery and overaging can occur during an off-load part of the test cycle, appear to produce creep to specified strains and fracture in times shorter than those corresponding on a net time basis to the case of steady load isothermal creep. Such cases are the steady temperature intermittent load cycles (cycles 1 and 2) and the out of phase combined intermittent loading and heating cycles (cycles 6 and 8). In all other cases the creep behavior approximates on a net time basis to the steady load isothermal creep behavior of 75S-T6 alloy at 300°F.

2. The order of the four cycles 1, 2, 6, and 8 with respect to their effect in causing acceleration of the creep of 75S-T6 alloy is not directly related to the amount of time per cycle which the specimen spends at the elevated temperature in the absence of load. A tentative explanation is based on the observation that the creep curve during one cycle on reapplication of the load appears to be of the form of the primary creep section of the standard creep curve. Further detailed experiments would be required before any judgment can be made on this hypothesis.

3. At 600°F, where overaging must occur in a short time early in the course of a creep test, and the material is never far removed from the fully recovered state, the creep behavior of aluminum alloy 75S-T6

when judged on a basis of net time at elevated temperature under load is approximately unaffected by intermittent conditions of heating and stressing.

4. At both 300°F and 600°F, the creep of 75S-T6 alloy under all the test conditions employed in the present series of tests may, to a good first approximation be represented by the functional equation

$$\varepsilon = F\left\{t\, f(\sigma)\right\}$$

where ε = total strain

t = total elapsed time

σ = stress

F = strain function

f = stress function.

The stress function, f, is only slightly dependent on strain over the range of stress 42,000 to 31,500 psi, and is apparently independent of the type of intermittent test cycle of temperature and stress. The equation can therefore be used to make effective predictions of the creep curves under an intermittent condition from a knowledge of the creep behavior under the normal steady load isothermal test conditions, and a single representative test at a standard stress under the intermittent condition.

5. A survey of a representative selection of available steady load isothermal creep data on a variety of materials shows that the above method of analysis is not generally applicable, being effective only in about one third of the cases, and then often being subject to limitations of stress and strain.

6. A survey of other creep data under intermittent conditions indicates that where the analysis can satisfactorily be applied to steady load isothermal creep data, it can usually, but not invariably, be applied

to intermittent data on the same material over the same stress, strain, and temperature ranges. The stress function of the equation given is then approximately independent of the type of intermittent test cycle, and data under intermittent conditions may be predicted as described above, permitting a great reduction in the amount of testing under intermittent conditions.

BIBLIOGRAPHY

1. G. R. Brophy and D. E. Furman, "Cyclic Temperature Acceleration of Strain in Heat Resisting Alloys", Transactions of the American Society of Metals, vol. 30, 1942, p. 1115.

2. H. S. Avery, Discussion on above paper "Cyclic Temperature Acceleration of Strain in Heat Resisting Alloys", Transactions of the American Society for Metals, vol. 30, 1942, p. 1130.

3. H. S. Avery and N. A. Mathews, "Cast Heat Resisting Alloys of the 16% Chromium, 35% Nickel Type", Transactions of the American Society for Metals, vol. 38, 1947, p. 980.

4. L. A. Shepard, C. D. Starr, C. D. Wiseman, and J. E. Dorn, "The Creep of Metals under Intermittent Stressing and Heating Conditions. Part 1 Intermittent Stressing", WADC Technical Report 53-336, Part 1.

5. L. A. Shepard, C. D. Starr, C. D. Wiseman, and J. E. Dorn, "The Creep of Metals under Intermittent Stressing and Heating Conditions. Part 2 Intermittent Heating", WADC Technical Report 53-336, Part 2.

6. L. A. Shepard, C. D. Starr, C. D. Wiseman, and J. E. Dorn, "The Creep of Metals under Intermittent Stressing and Heating Conditions. Part 3 Combined Intermittent Stressing and Heating", WADC Technical Report 53-336, Part 3.

7. G. J. Guarnieri, "Part 1. Intermittent Stressing and Heating Tests of Aircraft Structural Metals", WADC Technical Report 53-24, Part 1.

8. G. J. Guarnieri, "Part 2. Intermittent Stressing and Heating Tests of Aircraft Structural Metals", WADC Technical Report 53-24, Part 2.

9. L. A. Shepard, C. D. Starr, C. D. Wiseman, and J. E. Dorn, "Equipment for Testing the Creep Properties of Metals under Intermittent Stressing and Heating Conditions. Part 1", WADC Technical Report 52-101, Part 1.

10. L. A. Shepard, C. D. Starr, C. D. Wiseman and J. E. Dorn, "Equipment for Testing the Creep Properties of Metals under Intermittent Stressing and Heating Conditions. Part 2. Current Modifications", WADC Technical Report 52-101, Part 2.

11. American Society for Mechanical Engineers and American Society for Testing Materials, "Compilation of Available High Temperature Creep Characteristics of Metals and Alloys", 1938, Section A, Fig. 3A, p. 5.

12. John E. Dorn, "Some Fundamental Experiments on High Temperature Creep", Minerals Research Laboratory, Institute of Engineering Research, University of California (Berkeley), Technical Report Series No. 22, Issue No. 35, April 1954.

13. A. E. Flanigan, L. F. Tedsen, and J. E. Dorn, "Stress Rupture and Creep Tests on Aluminum Alloy Sheet at Elevated Temperatures", American Institute of Mining and Metallurgical Engineers Transactions, vol. 171, 1947, p. 213.

14. O. D. Sherby and J. E. Dorn, "The Effect of Cold Rolling on the Creep Properties of Several Aluminum Alloys", American Society for Metals, vol. 43, 1951, p. 611.

15. O. D. Sherby and J. E. Dorn, "Creep Properties of Two Tempers of 63S Extruded Aluminum Alloy", American Society for Testing Materials, vol. 51, 1951, p. 945.

16. O. D. Sherby and J. E. Dorn, "Effect of Annealing on the Creep Properties of 2S-O Aluminum Alloy", American Society for Testing Materials, vol. 51, 1951, p. 954.

17. A. T. Robinson, T. E. Tietz, and J. E. Dorn, "The Function of Alloying Elements in the Creep Resistance of Alpha Solid Solutions of Aluminum", American Society for Metals, vol. 44, 1952.

18. D. A. Oliver and G. T. Harris, "High Creep Strength Austenitic Gas Turbine Forgings", Institute of Marine Engineers (England), vol. 59, (No. 5) 1947, p. 79.

19. D. A. Oliver and G. T. Harris, "Some Proven Gas Turbine Steels and Related Developments", Iron and Steel Institute (England). Symposium on High Temperature Steels and Alloys for Gas Turbines, July 1952, p. 46.

20. H. W. Kirkby and C. Sykes, "Properties of Materials Intended for Gas Turbines", ibid. p. 81.

21. Henry Wiggin and Company, Birmingham, England, "The Nimonic Alloys". Handbook.

22. Howard C. Cross and Ward F. Simmons, "Heat Resisting Metals for Gas Turbine Parts", Symposium on Materials for Gas Turbines. American Society for Testing Materials, 1946.

23. G. J. Guarnieri, "Part 3. Intermittent Stressing and Heating Tests of Aircraft Structural Metals", WADC Technical Report 53-24 Part 3.